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Seattle Distribution System Corrosion Control Study. Volume 2 Tolt River Water Pilot Plant Study

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SEATTLE DISTRIBUTION SYSTEM CORROSION CONTROL STUDY
Volume II. Tolt River Water Pilot Plant Study

By

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Grant No. R 806686 010

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16. ABSTRACT

For 6 months, the Seattle Water Department conducted a corrosion treatment pilot plant study, obtaining data on the treatment of Tolt River water with lime/sodium carbonate, lime/sodium bicarbonate, and lime/bicarbonate/silicate. Continuous-flow pipe coupon tests were conducted to determine corrosion rates, penetration rates, and corrosion types for copper, galvanized steel and black steel pipes. Metal leaching tests were conducted using small diameter pipes. Research showed that using lime plus sodium carbonate, lime plus sodium bicarbonate, and lime plus bicarbonate plus silicate will significantly reduce corrosion in home plumbing systems. Copper and galvanized steel showed corrosion rate reductions of 85% and 24%, respectively, when lime plus sodium carbonate was used; 85% and 43% when lime plus sodium bicarbonate was used; and 83% and 49% when lime plus bicarbonate plus silicate was used. All the treatments significantly reduced lead, zinc and copper leaching in the metal leaching tests. Based on this pilot study, lime plus sodium carbonate treatment is recommended for the Cedar River water supply at an average dosage of 1.7 mg/L CaO. This dose should achieve an average distribution system pH of 7.9 and an alkalinity of 18 mg/L $CaCO_3$.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report presents the results obtained and conclusions drawn from pilot plant research on the corrosion treatment of an aggressive water supply. The data supports the conclusion that substantial corrosion reduction can be achieved by treatment.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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ABSTRACT

A study was conducted in Seattle, Washington, to evaluate the use of lime, sodium carbonate, sodium bicarbonate, and silicate in surface water supplies to control corrosion of plumbing materials. Continuous-flow pipe-coupon tests were used to test the effectiveness of three water treatments - addition of lime plus sodium carbonate, lime plus sodium bicarbonate, and lime plus sodium bicarbonate plus silicate. Three commonly used plumbing materials (copper, galvanized steel, and black steel) were tested for corrosion type and rate, penetration rate, and metal leaching. Corrosion rates were evaluated through weight loss, penetration rates were tested with pitting depth measurements, and corrosion films were analyzed by scanning electron microscope and energy dispersive X-ray diffraction techniques. Metal leaching tests were conducted using small-diameter pipes which exaggerate the test results and thus enable meaningful comparisons to be made in short-term tests. This method was developed by the Seattle Water Department for this study.

Results indicate that the use of any of the three treatments will significantly reduce corrosion in home plumbing systems. Copper and galvanized steel showed corrosion rate reductions of 85% and 24%, respectively, when lime plus sodium carbonate was used; 85% and 43% when lime plus sodium bicarbonate was used; and 83% and 49% when lime plus sodium bicarbonate plus silicate was used. All three treatments significantly reduced leaching of lead, zinc, and copper from the metal leaching loops. However, the leaching of lead and cadmium from galvanized pipe into standing water increased with treatment.

These tests confirm earlier pilot studies indicating that significant corrosion protection for plumbing materials can be affected by raising both the pH and alkalinity of surface water supplies. Treatment with lime plus sodium carbonate is recommended for the Tolt River water supply in view of the overall corrosion protection it affords to commonly used plumbing materials, its costs, and availability. A recommended average dosage of 2.0 mg/L of lime (CaO) and 9.0 mg/L of sodium carbonate (Na_2CO_3) at the Tolt Regulating Basin will increase pH and alkalinity to 8.3 and 14 mg/L (as $CaCO_3$), respectively. This dose should achieve an average distribution pH and alkalinity of 7.88 and 16 mg/L $CaCO_3$ for Tolt water after it passes through open distribution reservoirs and is rechlorinated.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

A.A.S.	-- atomic absorption spectrophotometry
^oC	-- degrees Celsius
cm	-- centimeters
cm^2	-- centimeters squared
EDAX	-- energy dispersive X-ray analysis
EIS	-- environmental impact statement
EPA	-- U.S. Environmental Protection Agency
fps	-- feet per second
ft^3/min	-- cubic feet per minute
gal	-- gallons
$[\text{Halogen} + SO_4^{=}]/\text{Alk}$	-- $[\text{halogen + sulfate}]$ / alkalinity ratio
in.	-- inches
ISWS	-- Illinois State Water Survey
L	-- liters

L/s	-- liters per second
MCL	-- maximum contaminant level
mgd	-- million gallons per day
mg/L	-- milligrams per liter
mg/cm^2	-- milligrams per square centimeter
mi	-- miles
mpy	-- mils per year
m^3/d	-- cubic meters per day
RPM	-- revolutions per minute
SEM	-- scanning electron microscopy
SWD	-- Seattle Water Department
yr	-- year
50/50 Pb-Sn	-- 50% lead, 50% tin solder
µg/L	-- micrograms per liter
µm	-- micrometers
µmhos	-- micromhos

SYMBOLS

C	-- carbon
$CaCO_3$	-- calcium carbonate
CaO	-- calcium oxide (lime)
Cd	-- cadmium
CO_2	-- carbon dioxide
Cu	-- copper
e^-	-- electron
Fe	-- iron
H^+	-- hydrogen ion
H_2CO_3	-- carbonic acid
HCO_3^-	-- bicarbonate
H_2O	-- water
HS^-	-- hydrogen sulfide ion
H_2S	-- hydrogen sulfide
HSO_4^-	-- bisulfate ion
HNO_3^-	-- nitric acid
$HZnO_2^-$	-- bizincate
Na_2CO_3	-- sodium carbonate

$NaHCO_3$	-- sodium bicarbonate
NH_4 Acetate	-- ammonium acetate
NH_4 Citrate	-- ammonium citrate
NH_4OH	-- ammonium hydroxide
O_2	-- oxygen
pe	-- -log $\{e^-\}$
pH	-- -log $\{H^+\}$
P_{H2}	-- Partial pressure of hydrogen
P_{O2}	-- Partial pressure of oxygen
S	-- sulfur
$SO_4^{=}$	-- sulfate
Zn^{++}	-- zinc ion
$ZnCO_3$	-- zinc carbonate
$ZnO_2^{=}$	-- zincate
$Zn(OH)_2$	-- zinc hydroxide
$Zn(OH)^+$	-- zincil ion
ZnS	-- zinc sulfide
$ZnSO_4$	-- zinc sulfate

CONVERSION FACTORS

Metric Unit	Multiplier	English Unit
cm	0.394	in.
cm^2	0.155	$in.^2$
m	3.28	ft
L	0.264	gal
L/s	118.5	ft^3/min
m^3/d	2.64×10^{-4}	mgd
km	0.577	mi

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SECTION 1

INTRODUCTION

SCOPE

This study is Volume II of a six-volume series presenting results of research conducted under the Seattle Distribution System Corrosion Control Study. Presented in this volume are the results of a pilot plant study for internal corrosion control in the Tolt distribution system. Volume I presents pilot test results and recommends specific chemical treatment for internal corrosion control in the Cedar distribution system. Volume III evaluates the potential of drinking water contamination from the corrosion of tin/antimony solder. Volume IV presents the results of a pilot plant study conducted to determine the effects of chemical treatment on old galvanized pipe. Volume V addresses the counteractive effects of disinfection (chlorination) and corrosion control (pH/alkalinity adjustment). Volume VI presents a laboratory electrochemical technique for corrosion rate determinations in drinking water.

BACKGROUND INFORMATION

Seattle Service Area

The Seattle Water Department (SWD) service area includes Seattle proper and also most of the metropolitan area. It extends from Edmonds on the north to just south of Des Moines, and easterly from Puget Sound to Lake Sammamish at the foot of the Cascade range. Nearly 1 million persons are served directly or indirectly by the SWD, which represents about 83% of the population of King County. Average total water consumption is 609,000 m^3/d, and summer peak day use has reached 1.3 million m^3/d. Approximately two-thirds of this water is sold directly to the SWD retail customers, and the remaining portion is delivered at wholesale rates to suburban water districts and municipalities, who in turn sell it to their direct service customers.

Water Sources

The primary sources of Seattle water are the Cedar and Tolt rivers on the western slope of the Cascade Mountains in eastern King County. These two rivers furnish high quality mountain water of unusual clarity. The Cedar River water supply system, which has been in operation since 1901, serves the southern region of Seattle and parts of South King County. The

Tolt, which was added to the City system in 1964, generally serves the area north of the Lake Washington Ship Canal and the water purveyors on the east side of Lake Washington. These two sources feed the distribution system from opposite ends, a feature that affords excellent hydraulic characteristics. Figure 1 illustrates the major facilities of the system.

Water Treatment

Currently, the treatment of both water supplies consists of intake screening, chlorination and fluoridation. Prior to distribution, the water is rechlorinated as it leaves the open in-town reservoirs to assure the free chlorine residual necessary to maintain adequate levels of disinfection. Compared to most other major water utilities in this country, the present treatment is minimal. Many utilities are required to extensively treat their water with coagulation and filtration techniques to render it safe to drink. The SWD's emphasis on watershed protection, together with the large storage reservoir system to meet demands during periods of high turbidity, has enabled Seattle to meet National Interim Primary Drinking Water Regulations[1] without major modifications to the existing facilities.

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Existing Facilities on the Tolt River System

The Tolt River system originates in a 54 square kilometer area watershed, which is narrow and steep and has been prone to slide activity. Ownership in the watershed is about equally divided between the Weyerhaeuser Company, the U.S. Forest Service and the SWD. Ten major streams feed the South Fork Tolt Reservoir, a 69 million cubic meter (m^3) man-made storage reservoir with a maximum pool elevation of 536 m. The water enters an 84 centimeter (cm) diameter, 7.7 kilometer pipeline through one of three intakes which are located at different depths in the reservoir. Upon discharge from the pipeline, water enters the pressure regulating basin, a 108,000 m^3 reservoir at an elevation of 231 m. The purpose of the pipeline and the regulating basin is to dissipate 305 m of head. Water then enters a 168 cm diameter transmission line where it is chlorinated and fluoridated and subsequently discharged into the Seattle distribution system.

Tolt Corrosion Treatment Facility

In July 1980, a bid to construct a new chemical treatment facility at the outlet from the Tolt Regulating Basin was accepted by the SWD. The treatment facility includes a lime silo, lime feeding and pumping equipment, and sodium carbonate feeding and pumping equipment. Additional space has been provided at the site for the addition of silicate treatment if needed. The facility is expected to be completed by November 1981.

Internal Corrosion Problem

Water quality deterioration in home and building plumbing systems is a major concern of the SWD. Through several projects that have examined the corrosivity of its water supplies, it is now well documented that corrosion, although not a concern in the distribution system, causes several problems in premise plumbing.[2] In addition to causing the obvious aesthetic problems

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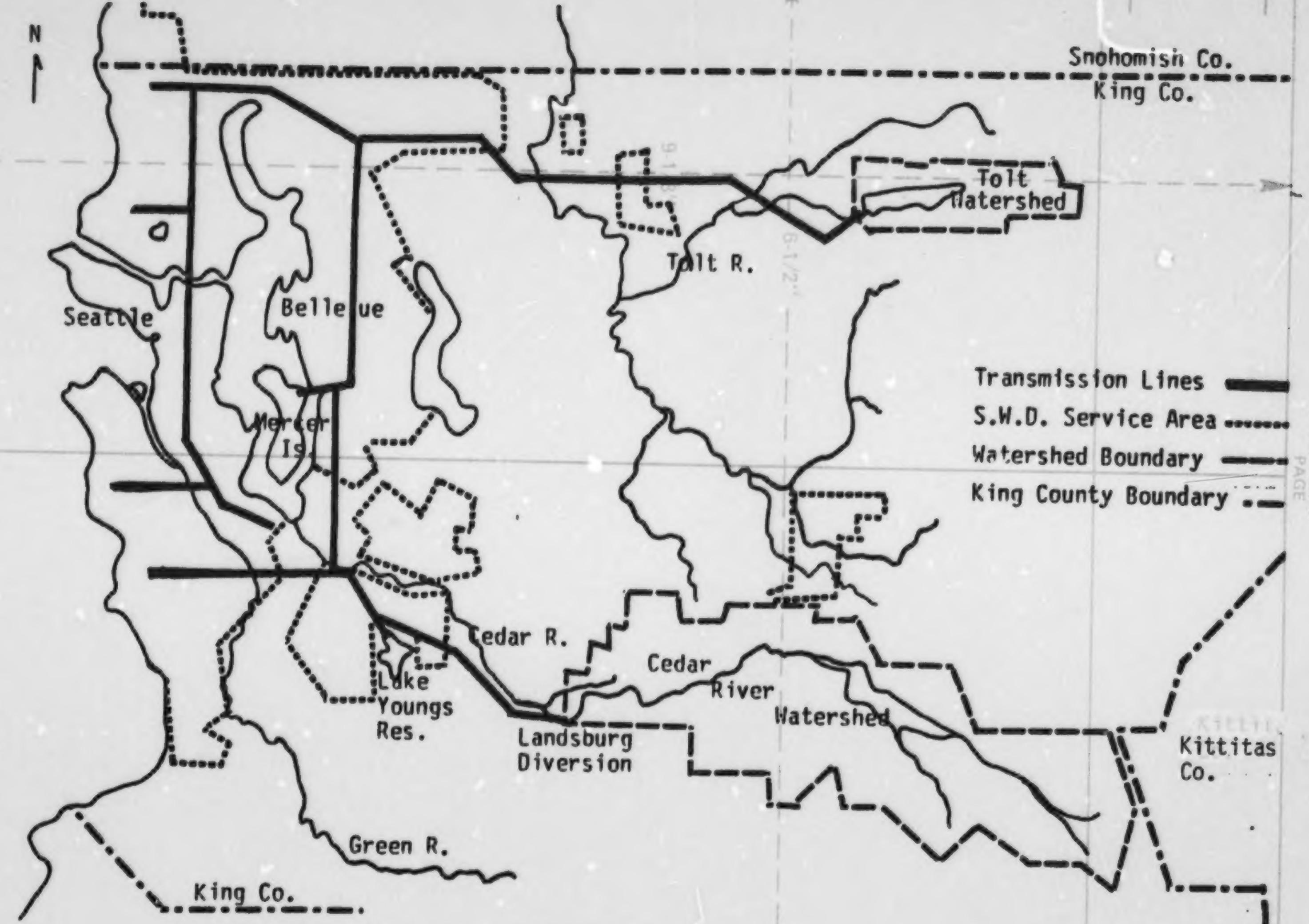

Figure 1. Major facilities of the Seattle distribution system.

of rusty water, red and blue staining and metallic tastes; plumbing corrosion is responsible for a sizable economic burden on Seattle homeowners and possibly some long-term health impacts to those with high environmental exposure to lead.

Aesthetics --

Customer complaints of rusty water, stained fixtures and metallic tastes are frequently received from within the Tolt water distribution system. This problem has been well documented by accurate complaint records and by a questionnaire survey conducted by SWD in 1973. The survey, which was distributed to 10% of all services within the direct service area, showed that 28.3% of customers in the Tolt water distribution system experienced corrosion-related problems.[3]

Economics --

Significant corrosion of piping occurs in the premise plumbing systems served by the Tolt supply. The average estimated life span of hot water galvanized and copper pipes is approximately 25 years. The forecasted 1978 average annual cost for maintaining serviceability in these pipes was estimated to be approximately $3.8 million.[4]

Health Impact --

Further evidence gathered since 1972 demonstrates that the levels of lead (Pb), copper (Cu) and iron (Fe) often exceed Maximum Contaminant Levels (MCL) in overnight standing Tolt tap water (Table 1).

TABLE 1. PERCENTAGE OF SAMPLES EXCEEDING EPA MAXIMUM CONTAMINANT LEVELS

		Primary Contaminants				Secondary Contaminants									
		Lead 0.05 mg/L		Cadmium 0.01 mg/L		Copper 1 mg/L		Iron 0.3 mg/L		Zinc 5 mg/L		Color 15 units		Manganese 0.05 mg/L	
Survey	Water Supply	R*	S†	R	S	R	S	R	S	R	S	R	S	R	S
EPA§ (1972)	Tolt	0	23	0	9	3	23	15	73	0	9	-	-	0	5
SWMS‡ (1974-75)	Tolt	0	10	0	0	1	9	19	76	0	1	24	87	0	10
	Cedar	0	16	0	2	0	10	8	60	0	3	0	56	0	0
RWQM# (1979-80)	Tolt	0	9	0	0	2	23	20	79	0	0	-	-	-	-
	Cedar	0	6	0	0	0	4	11	76	0	0	-	-	-	-

*R = Running cold water samples.
†S = Overnight standing cold water samples.
‡ = Seattle Water Metals Survey.
§ = Study of Corrosion Products in the Seattle Water Department Tolt Distribution System.[6]
# = Seattle's Residential Water Quality Monitoring.

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Cadmium (Cd) and zinc (Zn) were also found to increase after overnight standing in home plumbing; however, they rarely exceeded their MCL's.

Although the health impact of overnight standing water metal levels is not an acute problem, it would be desirable to reduce exposure to metals, especially lead and cadmium.

Causes of Corrosion

The corrosiveness of Tolt water results from several related factors, which include:

Acidity as indicated by low pH; the raw Tolt water pH is approximately 6.7; after chlorination and fluoridation, pH is reduced to a range of 5.8 to 6.2;

A dissolved oxygen concentration that is at saturated conditions;

Insufficient calcium and bicarbonate alkalinity in the water to form protective calcium carbonate films on pipe surfaces;

A relatively high [halogen + sulfate] / alkalinity ratio [(Halogen + $SO_4^{=}$) / Alk] of 2.5 which is an indicator of conditions favorable to pitting corrosion.

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In 1970, three factors combined to intensify the corrosiveness of both water supplies: (1) To decrease the occurrence of positive bacteriological samples within the distribution system, the chlorine dosage at the open reservoir outlets was increased. (2) At the request of the U.S. Public Health Service, ammoniation of the water supply was stopped to enable a free chlorine residual to be maintained throughout the distribution system. This change from combined chlorination to free chlorination was implemented to provide quicker, more effective disinfection of the unfiltered water supply. (3) Based on a vote of the Seattle citizens in 1968, fluoridation with hydrofluosilicic acid began in 1970.

Internal Corrosion Study[4]

In December 1975, the City of Seattle retained a consulting engineering firm to perform a detailed analysis of the corrosion problem and to recommend possible solutions. The Internal Corrosion Study, which included a nine-month pilot plant investigation, confirmed the corrosiveness of Seattle water, the causes of corrosion, and the impacts associated with the corrosive water. The study also evaluated alternative measures to reduce the corrosiveness of the water supply. Corrosion reduction alternatives investigated included alternative methods of disinfection and fluoridation, blending with groundwater supplies, and the addition of corrosion inhibitor chemicals.

Based on the findings of the consultant study and the conclusions of pilot plant investigations, an Internal Corrosion Control Management Plan was developed. Because the very low level of mineral solids, pH, and alkalinity constitute the major causes of the waters' corrosiveness, the proposed

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plan was designed to correct the natural deficiency of minerals in Seattle's Tolt water. The natural deficiency of calcium, silicate and carbonate/bicarbonate alkalinity ions was proposed to be corrected by the addition of lime, sodium bicarbonate, and possibly sodium silicate, to achieve the water shown in Table 2.

The combination of lime and bicarbonate was chosen because higher levels of alkalinity can be reached at pH 8.3 and a higher pH can be maintained in the distribution system with this combination than with combinations of other commonly used corrosion inhibitors, specifically lime and sodium carbonate. Although the consultant recommended lime and sodium bicarbonate treatment, the actual chemical combination was not extensively tested in their pilot studies.

STUDY OBJECTIVES

The formal objective of this research effort was to determine whether lime plus sodium carbonate treatment, lime plus sodium bicarbonate treatment, or lime plus sodium bicarbonate plus silicate treatment is best in controlling internal plumbing corrosion in Tolt water. The scope of work included:

1. Determining the corrosion rates, penetration rates and corrosion types from galvanized steel, copper and black steel piping materials exposed to control, lime/sodium carbonate, lime/sodium bicarbonate, and lime/sodium bicarbonate/silicate treated water.

2. Determining tap water metal leaching associated with each treatment from copper pipe; 50% lead, 50% tin solder (50/50 Pb-Sn); 95% tin, 5% antimony solder (95/5 Sn-Sb); and galvanized steel pipe.

3. Predicting increases or decreases in residential pipe life spans associated with each treatment.

TABLE 2. RECOMMENDED WATER QUALITY FOR THE TOLT SUPPLY

Parameter	Existing Water Quality	Proposed Water Quality with Corrosion Treatment
pH	5.8 - 6.2	7.8 - 8.3*
Total Alkalinity, mg/L $CaCO_3$	2.0	20 - 25
Halogen + $SO_4^{=}$/Alk Ratio	2.5	< 0.5

*A pH of 8.3 was determined as the practical upper limit for pH adjustment. This pH limit was chosen because pH > 8.3 in the Tolt supply may cause excessive trihalomethane formation[4] and at pH above 8.3, the disinfection power of free chlorination is considerably reduced.[7]

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4. Establishing the required optimal full-scale chemical dosages for both treatments.

SCOPE OF STUDY

During the periods from November 9, 1979, to November 29, 1979, and May 1, 1980, to December, 1980, four continuous flow corrosion test apparatus (control, lime/carbonate, lime/bicarbonate, and lime/bicarbonate/silicate treatment) were operated at Seattle's Foy Pump Station. (The test apparatus was not in operation from November 30, 1979, to April 30, 1980, because the Tolt supply was shut down due to high turbidity in the South Fork Tolt Reservoir.) This test site was chosen within the Tolt distribution system in order to conduct the corrosion testing with the same water quality as is delivered to the SWD customer.

The corrosion coupon tests used documented average corrosion rates based on weight loss, penetration rates based on pit depths, and corrosion types based on visual observations. Coupons were made of 2.54 cm diameter pipe segments of iron, galvanized steel and copper.

Metal leaching tests for Cu, Pb, Cd, Sb, and Zn were performed on separate 0.635 cm diameter pipe sections attached to the main test apparatus. This is a new method which has been developed by SWD for this study. Also, scanning electron microscopy (SEM) and X-ray diffraction analyses were conducted on the corrosion films which formed on the metal leaching test sections.

STUDY ELEMENTS

The study consisted of the following three primary elements that included various secondary topics.

Corrosion Control Treatment

1. Treatment effectiveness.
2. Comparison of treatments.
3. Comparison of treatment costs.

Methods of Analysis

1. Metal coupon analysis techniques.
2. Development of metal leaching evaluation method.
3. Scanning electron microscopy and X-ray diffraction analysis.

Corrosion Characterization

1. Corrosion types
2. Determination of corrosion rates and penetration rates.
3. Plumbing life spans.
4. Metal leaching.
5. Corrosion films.

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SECTION 2

CONCLUSIONS

COMPARISON OF CHEMICAL TREATMENT ALTERNATIVES

A comparison of the effectiveness of the chemical treatments used in the Tolt River Pilot Plant Study is presented in Table 3.

TABLE 3. REDUCTION IN CORROSION EFFECTED BY TREATMENT (%)

	Copper Corrosion		Copper and Solder Corrosion		Galvanized Steel Corrosion				Black Steel Corrosion	
Treatment*	Corrosion Rate by Weight Loss	Copper Leaching	Lead Leaching from Lead/Tin Solder	Lead Leaching from Tin/Antimony Solder	Corrosion Rate by Weight Loss	Zinc Leaching	Lead Leaching	Cadmium Leaching	Corrosion Rate by Weight Loss	Pitting
A	0	0	0	0	0	0	0	0	0	0
B	85	67	80	48	24	61	-105	-35	-33	-10
C	85	72	55	89	43	51	-128	-35	-20	2
D	83	78	69	99	49	38	-112	-47	8	-20

*Identification: A = Control
B = Lime/Sodium Carbonate
C = Lime/Sodium Bicarbonate
D = Lime/Bicarbonate/Silicate

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Each criterion is explained below:

1. Corrosion rate by weight loss - The percent reduction of corrosion rates based on weight loss.
2. Pitting - The percent reduction of penetration rates based on pitting data.
3. Metal leaching - The average reduction of metal concentrations during the entire testing period.

Table 3 indicates the following conclusions for each chemical treatment alternative.

Lime/Sodium Carbonate Treatment

Based on the matrix analysis of alternatives presented in Section 6, the lime/carbonate treatment produced the most cost effective protection against corrosion and metal leaching. This treatment produced better reductions than lime/bicarbonate and lime/bicarbonate/silicate treatments for zinc leaching from galvanized pipe and lead leaching from lead/tin solder. Approximately equal reductions in copper corrosion were achieved with all three treatments.

Lime/carbonate treatment is by far the least expensive treatment; and because both lime and sodium carbonate can be used alone for pH control, a lime/carbonate system can maintain a more consistent water quality during periods of equipment breakdown.

Lime/Sodium Bicarbonate Treatment

The lime/bicarbonate treatment did not produce the best results in any one category; however, it did produce better reductions than the lime/carbonate treatment in three evaluation criteria: galvanized steel corrosion rates, copper leaching from copper pipe and lead leaching from tin/antimony solder.

Lime/Bicarbonate/Silicate Treatment

The lime/bicarbonate/silicate treatment demonstrated the best reductions in four evaluation criteria: copper leaching from copper pipe, lead leaching from tin/antimony solder, and corrosion rates from galvanized steel and black iron. Although the addition of silicate produced larger corrosion reductions in these evaluation criteria, the added expense of feeding silicate is not justified.

No Treatment

The control tests demonstrated greater corrosion rates and metal leachate levels than the treatment tests with three exceptions: black steel corrosion rates, and lead and cadmium leaching from galvanized pipe.

PROPOSED CHEMICAL TREATMENT

The results of the pilot plant test program presented previously demonstrate that lime/sodium carbonate treatment is the most appropriate chemical treatment for the Tolt water supply. Table 4 details the recommended chemical dosages, target water quality and chemical costs.

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TABLE 4. RECOMMENDED CHEMICAL DOSAGES, TARGET WATER QUALITY AND CHEMICAL COSTS

Item	Present Conditions	With Lime Plus Sodium Carbonate Treatment
Treatment Plant CO_2	6.0*	0.0
Treatment Plant pH	6.0*	8.3
Average Total Alkalinity, $CaCO_3$	2.5*	14.0
Atmospheric Equilibrium pH @ 15°C	6.95	7.75
Minimum Distribution pH	5.6*	7.45†
Estimated Average Distribution pH	5.9*	7.85
Average Distribution Conductivity	27.0*	42.0
(Halogen + $SO_4^{=}$)/Alk Ratio	2.5-5.9†	0.45-1.1†
Average Lime Dosage (CaO), mg/L	-	1.7
Average Sodium Carbonate Dosage (Na_2CO_3), mg/L	-	9.0
Chemical Cost per Year ($)	-	147,000‡

*Based on SWD water quality monitoring data.
†By calculation.
‡Based on cost of chemicals delivered to Tolt Regulating Basin - June 1981.

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SECTION 3

RECOMMENDATIONS

GENERAL

This section of the report makes recommendations regarding additional research needs and further evaluations in the area of corrosion control.

SEATTLE WATER DEPARTMENT

The SWD should:

- Implement lime plus sodium carbonate treatment of the Tolt River source to increase pH and alkalinity to reduce corrosion of premise piping.
- Determine to what extent chemical treatment for corrosion control decreases the disinfection power of free chlorine.
- Monitor bacteriological water quality in the Tolt distribution system before and after the implementation of full-scale treatment.
- Evaluate the possibility of trihalomethane formation in Tolt water with respect to chemical treatment.
- Determine whether corrosion treatment will cause post-precipitation problems in the Tolt system.

U.S. ENVIRONMENTAL PROTECTION AGENCY

The EPA should:

- Develop a standard corrosion test loop for corrosion analysis of drinking water.
- Develop a method for the determination of metal leaching from plumbing materials.
- Publish a state-of-the-art manual for corrosion control of drinking water.

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SECTION 4

EQUIPMENT DESIGN AND OPERATION

PILOT TEST APPARATUS

Continuous Flow Test Unit

The continuous flow test unit illustrated in Figure 2 followed the descriptions for ASTM D2688-C-75, otherwise known as the Illinois State Water Survey (ISWS) test apparatus.[8] This same basic equipment was used earlier by the consultants[4] for evaluations of lime/soda ash, lime/$Zn\text{-}PO_4$, and NaO/SiO_2 on Cedar and Tolt water supplies. Each complete loop contains four 10.2 cm long pipe segment coupons (2.54 cm diameter) of copper, galvanized iron, and steel pipe that meet ASTM Standard C2688-C-75. The coupons are placed within the loop in order of increasing nobility.

A velocity of 0.30 m/s was maintained through the 2.5 cm diameter pipe coupons. Flows through the loops were held stable through the use of a constant head reservoir with approximately 3.7 m head. The reservoir was constructed of a 1.2 m section of 15.2 cm diameter cast iron pipe with a welded plate over one end. Four 1.9 cm outlets were tapped into the base and a 1.6 cm black rubber hose was run to the test loops. The overflow was attached 0.30 m from the top to provide a constant surface level.

Chemicals were fed by seven AMF CUNO diaphragm pumps. The chemicals used were hydrated lime [$Ca(OH)_2$], sodium carbonate ($NaCO_3$), sodium bicarbonate ($NaHCO_3$), and N grade liquid sodium silicate (8.9% NaO/28.7% SiO_2). Feed solutions of the full strength chemicals [170 g $Ca(OH)_2$/151 L; 600 g Na_2CO_3/151 L; 4.2 kg $NaHCO_3$/151 L; 960 mL $Na_2\text{-}SiO_2$/151 L] were mixed in plastic buckets. The feed solutions were then pumped from the solution buckets into the test units just before static mixers.

Metal Leaching Test Loops

In addition, short sections 25-51 cm of 0.635 cm pipe were attached to the continuous flow test units for comparison of Cu, Pb, Zn, Cd, and Fe leaching under the three alternative treatments. The leaching pipe sections were made of copper, copper plus 50/50 Pb-Sn solder, copper plus 95/5 Sn-Sb, galvanized steel (new), and black iron pipe. Two velocities were used (0.12 m/s and 0.18 m/s) in establishing corrosion films in the metal leaching sections. Dissolved metals were determined after periodic 22 to 24 hour contact with test water in the laboratory.

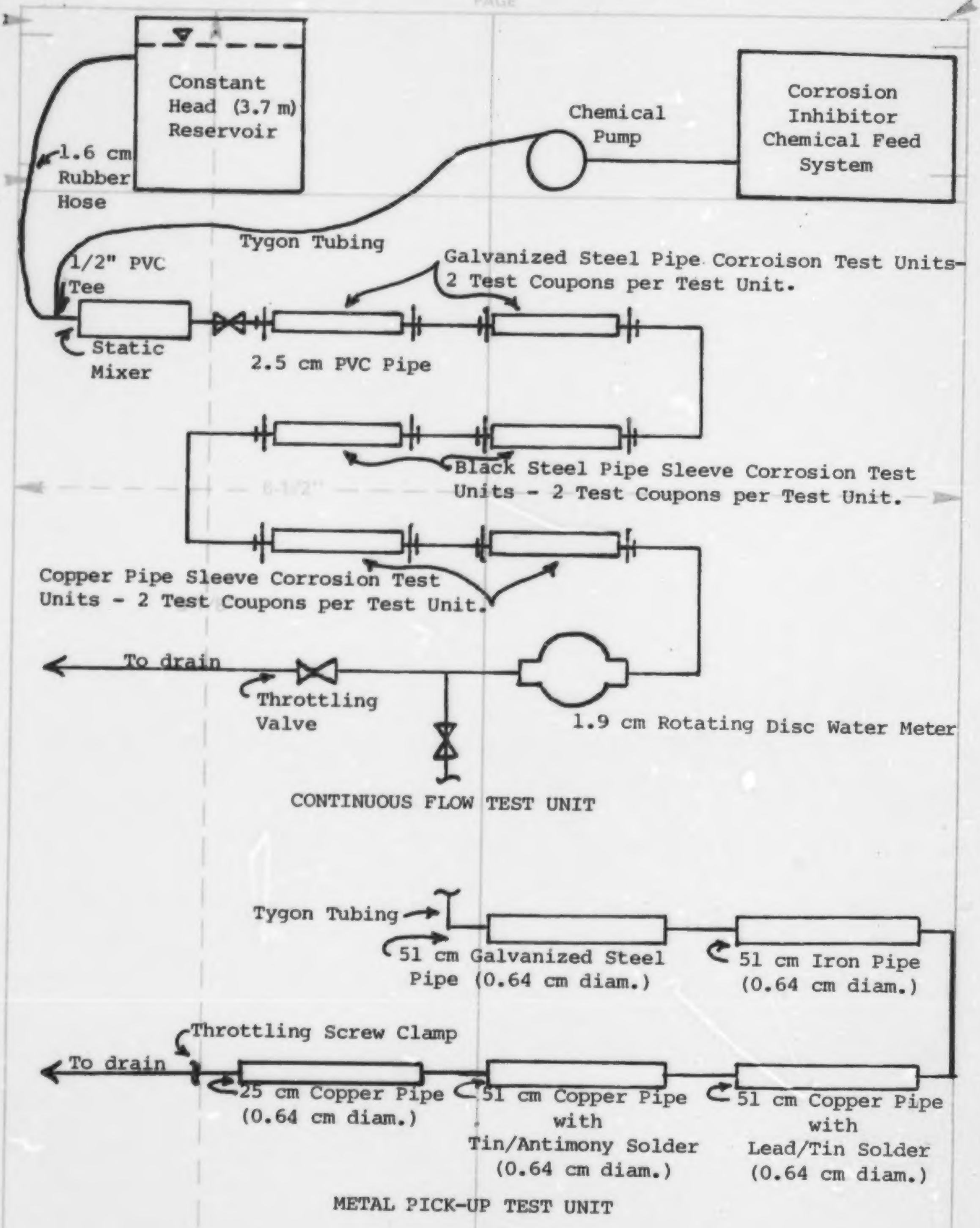
Constant Head (3.7 m) Reservoir
Corrosion Inhibitor Chemical Feed System
Chemical Pump
1.6 cm Rubber Hose
Tygon Tubing
1/2" PVC Tee
Galvanized Steel Pipe Corroison Test Units-2 Test Coupons per Test Unit.
Static Mixer
2.5 cm PVC Pipe
Black Steel Pipe Sleeve Corrosion Test Units - 2 Test Coupons per Test Unit.
Copper Pipe Sleeve Corrosion Test Units - 2 Test Coupons per Test Unit.
To drain
Throttling Valve
1.9 cm Rotating Disc Water Meter
CONTINUOUS FLOW TEST UNIT
Tygon Tubing
51 cm Galvanized Steel Pipe (0.64 cm diam.)
51 cm Iron Pipe (0.64 cm diam.)
Throttling Screw Clamp
To drain
25 cm Copper Pipe (0.64 cm diam.)
51 cm Copper Pipe with Tin/Antimony Solder (0.64 cm diam.)
51 cm Copper Pipe with Lead/Tin Solder (0.64 cm diam.)
METAL PICK-UP TEST UNIT

Figure 2. Pilot plant flow schematic.

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The construction of the 0.64 cm copper pipe with the 50/50 Pb-Sn and 95/5 Sn-Sb solder can be seen in Figure 3. This design allows for uniform surface areas of Cu and solder with intimate contact between the pipe and the solder. It exaggerates the lead leaching levels found in soldered copper pipe and therefore promotes meaningful comparison of the treatments.

Small diameter pipes were chosen for their high surface area to volume ratio, ease of manipulation, and flow control.

CHEMICAL TREATMENT

The test treatment conditions were chosen to simulate average distribution system levels of pH and alkalinity. Carbon dioxide (CO_2) uptake in open distribution reservoirs and conversion of bicarbonate to CO_2 by post-reservoir chlorination will lower pH and alkalinity from treatment plant levels. Laboratory tests (presented in Appendix A) were performed to estimate these changes. Table 5 presents the expected average distribution water quality with lime/carbonate, lime/bicarbonate, and lime/bicarbonate/silicate treatments.

SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy was performed by the Materials Analysis Center of the University of Washington's Department of Mining, Metallurgical and Ceramic Engineering.

The Center has a Cambridge Mark IIA Scanning Electron Microscope (SEM) capable of 200 Angstrom resolution, which was used in the secondary electron emission mode. The instrument has useful magnification to 50,000X and is unique in that its large depth of focus allows unusual observation and photography of three-dimensional structures not possible with other microscopic techniques.

The SEM is equipped with the EDAX Energy Dispersive X-Ray Detector for elemental analysis from fluorine to uranium in the atomic table. Qualitative analysis in the SEM mode was conducted with spectra generation typically less than a minute.

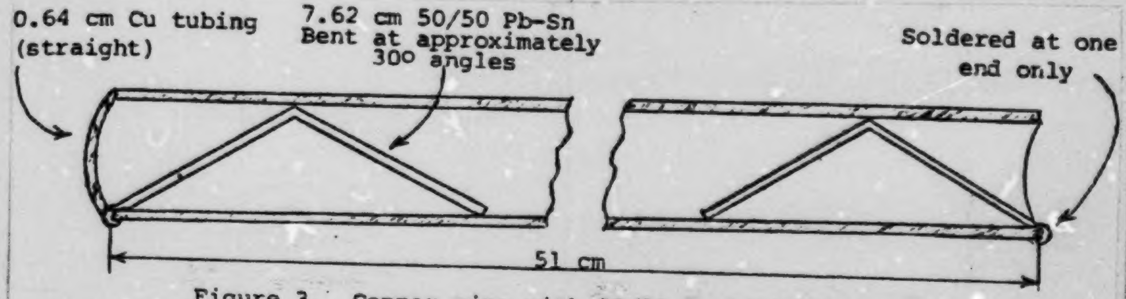
0.64 cm Cu tubing (straight)
7.62 cm 50/50 Pb-Sn Bent at approximately 30° angles
Soldered at one end only
51 cm

Figure 3. Copper pipe with 50/50 lead/tin solder.

TABLE 5. TOLT SUPPLY PILOT TEST CONDITIONS

Item	Loop #1 Control, Tolt Distribution	Loop #2 Lime + Soda Ash	Loop #3 Lime + Bicarbonate	Loop #4 Lime + Bicarbonate + Silicate
pH	5.8-6.2	7.85	7.95	7.95
Alkalinity ($mg/L\ CaCO_3$)	2.0	14.5	21	21
Chlorine Residual (mg/L)	~.2-.4	~.2-.4	~.2-.4	~.2-.4
Lime Dosage, CaO (mg/L)	0	1.5	4.5	3.5
Na_2CO_3 Dosage (mg/L)	0	10.0	0	0
$NaHCO_3$ Dosage (mg/L)	0	0	20.0	20.0
NaO/SiO_2 Dosage (mg/L as SiO_2)	0	0	0	4

Mounting of the specimens and subsequent coating in a vacuum evaporator was performed by the Center. The specimens were coated with a 250 to 300 Angstrom layer of gold or palladium in order to provide a conductive surface.

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SECTION 5

ANALYSIS AND PROCEDURES

METAL PIPE COUPON ANALYSIS

Corrosion Rates

Average corrosion rates were calculated by a two-step process: (1) Weight loss in milligrams per square centimeter (mg/cm^2) versus time was plotted for each metal and treatment; (2) the least squares slope ($mg/cm^2/day$) of the last three usable points of the weight loss curve was calculated and converted to mils per year (mpy). The calculated slope is a tool for comparison and except for copper, is only an approximation of long-term corrosion rates. For copper, the relationship between weight loss and time is linear, therefore corrosion rate is constant. For galvanized steel and iron, corrosion rates decrease with time and therefore can only be approximated.

Penetration Rates

Penetration rates were determined for the black steel coupons. The coupons were split into quarters and the pit depths were measured using either a pointed tip micrometer or a binocular microscope with a graduated fine focus adjustment. Penetration rates were then calculated in mpy based on the average of the ten deepest pits on each specimen.

Penetration rates were not determined for the galvanized steel coupons because an uneven galvanized layer on the coupons and a general thinning type corrosion caused large inaccuracies in pit depth measurements.

Metal Coupon Preparation

Coupons were prepared as directed in ASTM D2688-C-75[8] except as follows: They were scrubbed with non-chlorinated Bon Ami cleanser, rinsed with water, rinsed with denatured alcohol, and finally rinsed with alcohol/acetone/xylene. Prepared coupons were stored in a desicator.

Prior to insertion in the loops, the coupons' outer surfaces were coated with a very light film of silicone grease. They were then sealed in plastic holders with silicone seal gasket material at each end to prevent water from contacting the outer surface of the coupons. Coupons were identified by punching a letter-number code on the outside.

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Post-Exposure Cleaning Procedure

Post-exposure cleaning procedures were as follows:

1. The coupons were scraped with a plastic spatula and/or scrubbed with Bon Ami and a brush to remove loose deposits;
2. This was followed by chemical cleaning per the recommended procedures given in Corrosion Testing Procedures:[9]

    I. Copper: Scrubbing with Bon Ami only.

    II. Iron: 20% NH_4 CITRATE/10% NH_4OH at 70-75°C for 10 minutes; repeat Step #1.

    III. Galvanized Iron: Saturated NH_4 ACETATE for 10 minutes (room temperature); repeat Step #1.

3. Final washing in alcohol/xylene/acetone solvent, air dry, desicate.

METAL LEACHING TESTS

The metal leaching test loop sections were periodically removed during the study. The pipe sections were filled with test water from their respective loops, the ends were sealed with parafilm and then allowed to stand horizontally at 24°C for 24 hours. After this period, the water was filtered through a 0.45 µm Millipore membrane filter, preserved (.5% HNO_3 in Pyrex) and analyzed for metals by flame and flameless atomic absorption spectrophotometry (A.A.S.) according to Methods for Chemical Analysis of Water and Wastes.[10] Background metal concentrations were determined after passing the test waters through the same filtration apparatus, and these values were subtracted from the levels found after leaching. Metal losses via membrane filtration were determined and are presented in Appendix D.

Table 6 lists the pipe types, metals analyzed and analysis techniques.

QUALITY CONTROL

Daily pH and flow measurements and adjustment, and apparatus maintenance were performed to provide quality control over the test conditions. To document Na_2CO_3 feed in Loop #2 and $NaHCO_3$ feed in Loops #3 and #4, alkalinity and sodium analyses were performed weekly. Silicate tests were also conducted weekly to document SiO_2 feed in Loop #4. All measurements were performed according to "Standard Methods."[11] Quality assurance data is summarized in Appendix B.

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TABLE 6. PIPE TYPES, LEACHED METALS ANALYZED AND ANALYSIS TECHNIQUES

Metal Tested	Analysis Method	Test Pipe Section
Pb, non-filterable	Flameless A.A.S.*	Galvanized; Cu; Cu + 50/50 Pb-Sn solder; Cu + 95/5 Sn-Sb solder.
Sb, " "	"	Cu + 95/5 Sn-Sb solder.
Cd, " "	"	Galvanized; Cu + 50/50 Pb-Sn solder.
Cu, " "	Flame A.A.S.	Cu; Cu + 50/50 Pb-Sn solder; Cu + 95/5 Sn-Sb solder.
Zn, " "	"	Galvanized.

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SECTION 6

RESULTS AND DISCUSSION

METAL COUPON TESTS

Copper

Copper corrosion in Tolt water is of a uniform thinning nature, with numerous, very small, shallow pits. Corrosion rates in Tolt water stabilize in several weeks and only very thin corrosion films are formed. For these reasons, average coupon corrosion rates based on weight loss are an excellent approximation of the actual premise plumbing corrosion rates.[3]

Copper weight loss versus time is presented in Figure 4. Corrosion rates generated from this data indicate that each treatment reduced the corrosion rate by approximately 85%, thereby extending copper pipe life by better than a factor of 6 (see Table 7). The lime/soda ash test loop experienced more chemical feed pump problems than the other loops, resulting in

TABLE 7. COPPER CORROSION RATES AND % REDUCTIONS & PIPING LIFE PREDICTIONS

Treatment	Slope* ($mg/cm^2/day$)	Corrosion Rate mpy†	Corrosion Rate % Reduction	Average Piping Life‡ (Years)
Control	0.046	0.74	0	25
Lime/Sodium Carbonate	0.0071	0.11	85	170
Lime/Sodium Bicarbonate	0.0069	0.11	85	170
Lime/Sodium Bicarbonate/ Silicate	0.0077	0.12	83	150

*Slope of least squares fit of all data points.
†Slope x 16.1 (density factor).[12]
‡Based on Kennedy Engineers[4] original pipe life estimate for Type M copper, hot water service.

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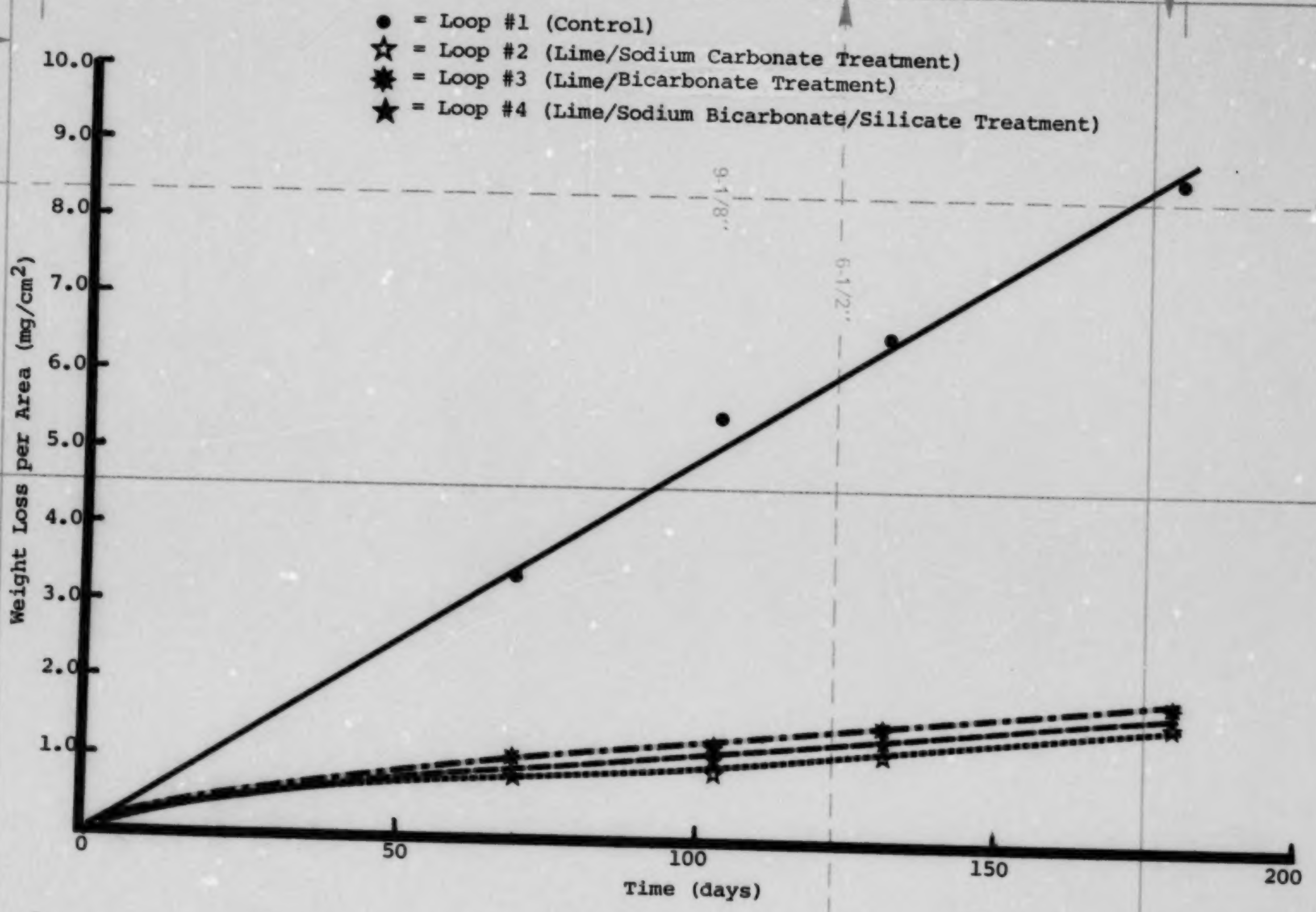

Figure 4. Tolt pilot plant test results - copper coupons weight loss.

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a lower average pH than was desired. This very probably caused poorer relative protection than it would have, had pH 7.85 been maintained.

Iron

The weight loss and pitting results for iron are presented in Figure 5 and Appendix C. Anomolous results clouded much of the findings for weight loss and penetration rates and thus the results in Tables 8 and 9 cannot be presented with the same certainty as the copper specimens.

TABLE 8. IRON COUPON WEIGHT LOSS RESULTS

Treatment	Slope (mg/cm^2/day)	Corrosion Rate (mpy)*	% Reduction
Control	.344	6.29	0
Lime/Soda Ash	.456	8.34	-33
Lime/Sodium Bicarbonate	.412	7.54	-20
Lime/Sodium Bicarbonate/ Silicate	.316	5.78	8

*mpy = Slope x 18.3 (density factor).[12]

TABLE 9. IRON COUPON PENETRATION RATES AND % REDUCTION

Treatment	Penetration Rate (mpy)	% Reduction (mpy)	% Area Attacked
Control	44.6	-	60
Lime/Soda Ash	49.1	-10	60
Lime/Sodium Bicarbonate	43.7	2	60
Lime/Sodium Bicarbonate/ Silicate	53.7	-20	40

*Based on average of last three data points.

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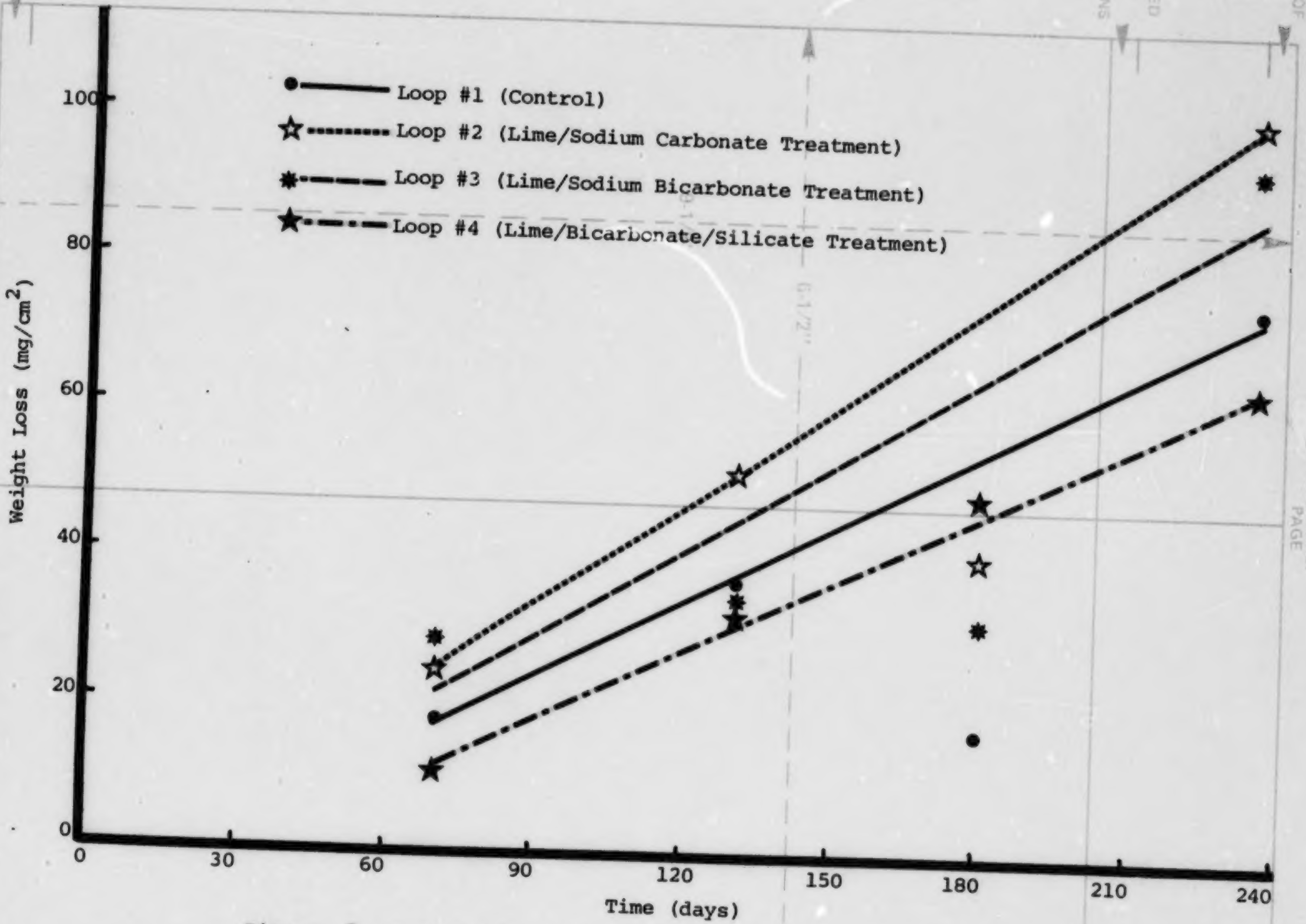

Figure 5. Tolt pilot plant test results - iron coupons weight loss.

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The iron data indicate a slight corrosion rate reduction for lime/bicarbonate/silicate treatment based on weight loss and for lime/bicarbonate treatment based on pitting. These results point out that little improvement will follow corrosion treatment for iron or old galvanized steel pipes which have iron exposed. Previous studies have found only slight benefits for iron pipe due to treatment.[4]

The results of the iron weight loss and penetration tests were not conclusive for various reasons:

1. An error was made in cleaning of the third set of coupons. The coupons were treated with the zinc cleaning solution, which resulted in lowered weight loss results. The data generated from these coupons was omitted from the corrosion rate calculations.
2. The type of coupons used for this test proved very difficult to clean. Substantial corrosion deposits remained on the coupons after the cleaning procedure.
3. The surface texture of the coupons varied significantly from coupon to coupon. As evidenced in Appendix C, this resulted in large variances in the pitting analysis results.

Based on these considerations, it is recommended that a different type of coupon be used for future iron corrosion testing. A coupon which has an outer surface exposed, instead of an inner surface, is much easier to clean and can also be machined to produce a uniform and consistent surface texture.

Galvanized Steel

The galvanized steel pipe specimens demonstrated general even corrosion. Only on the control specimens did the corrosion penetrate the galvanized layer and for this reason, pit depth data was only obtainable from the control loop. It should be noted that the data presented here is representative of new galvanized pipe corrosion and not representative of older (> 2-5 years) pipe, which has both iron and zinc exposed to the water. Once the galvanized layer is penetrated and much of the galvanizing removed, the corrosion of galvanized pipe is similar to the corrosion of iron pipe.

As shown in Figure 6 and Table 10, all treatments produced reductions in corrosion rates. The third set of data points was not included in the corrosion rate calculations becasue an error was made in the cleaning of the coupons. The best results were achieved with lime/bicarbonate/silicate treatment. The poorer performance of the lime/sodium carbonate treatment was probably due in part to operational problems. Lower average pH and alkalinities were achieved in that test loop because of frequent lime feed disruptions caused by air binding of the chemical feed pump. It is expected that corrosion rates can be reduced by approximately 40% with consistent lime/sodium bicarbonate treatment.

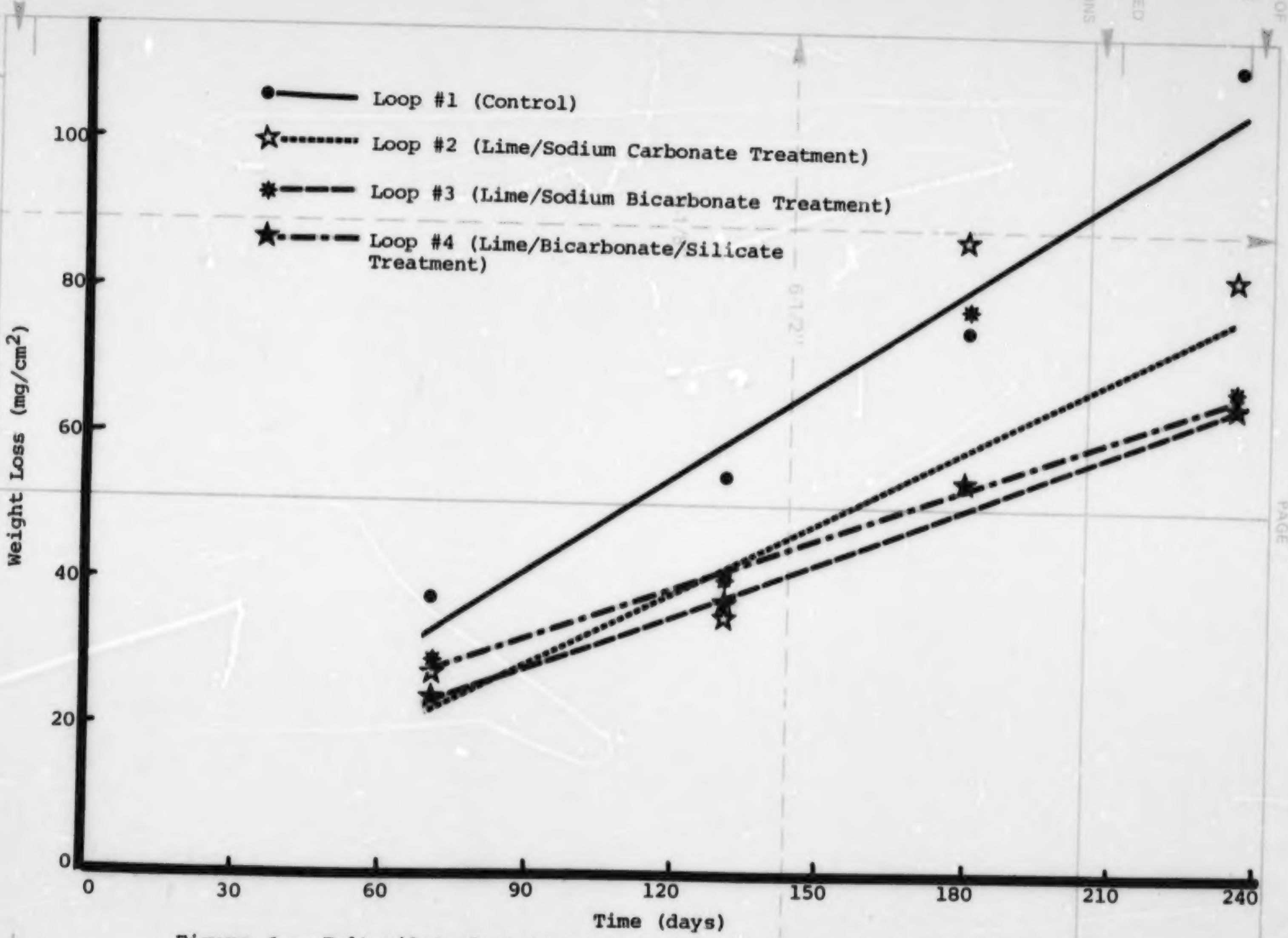

Figure 6. Tolt pilot plant test results - galvanized steel coupon weight loss.

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TABLE 10. GALVANIZED PIPE COUPON CORROSION RATES AND % REDUCTION

Treatment	Slope (mg/cm/day)	Corrosion Rate (mpy)*	% Reduction
Control	.228	4.61	0
Lime/ Sodium Carbonate	.174	3.51	24
Lime/Sodium Bicarbonate	.129	2.61	43
Lime/Sodium Bicarbonate/ Silicate	.117	2.36	49

*mpy = Slope (mg/cm^2/day) x 20.2 (density factor).[12]

METAL LEACHING

The treated water's impacts on leaching of lead, cadmium, copper and zinc during 24 hour contact time with plumbing materials was determined as described in Section 5. The velocities through the test sections were set at 0.12 m/s for the first 145 days of testing. Since the leach testing was intended to show exaggerated metal levels for best comparison of treatments, and since the copper and lead levels from the copper plus solder control section stabilized to levels no greater than many Seattle residential tap samples, the velocities were increased to 0.18 m/s for the remainder of the test. The velocity increase was designed to accelerate corrosion but in most instances did not.

Copper Pipe

Copper pipe was analyzed for copper and lead leaching. The copper leaching results are summarized in Figure 7. Average % reductions in copper leaching are presented in Table 11.

TABLE 11. METAL LEACHING REDUCTION RESULTS FROM COPPER PIPE

Treatment	Average % Reduction of Dissolved Copper
Control	0
Lime/Sodium Carbonate	68
Lime/Bicarbonate	72
Lime/Bicarbonate/Silicate	78

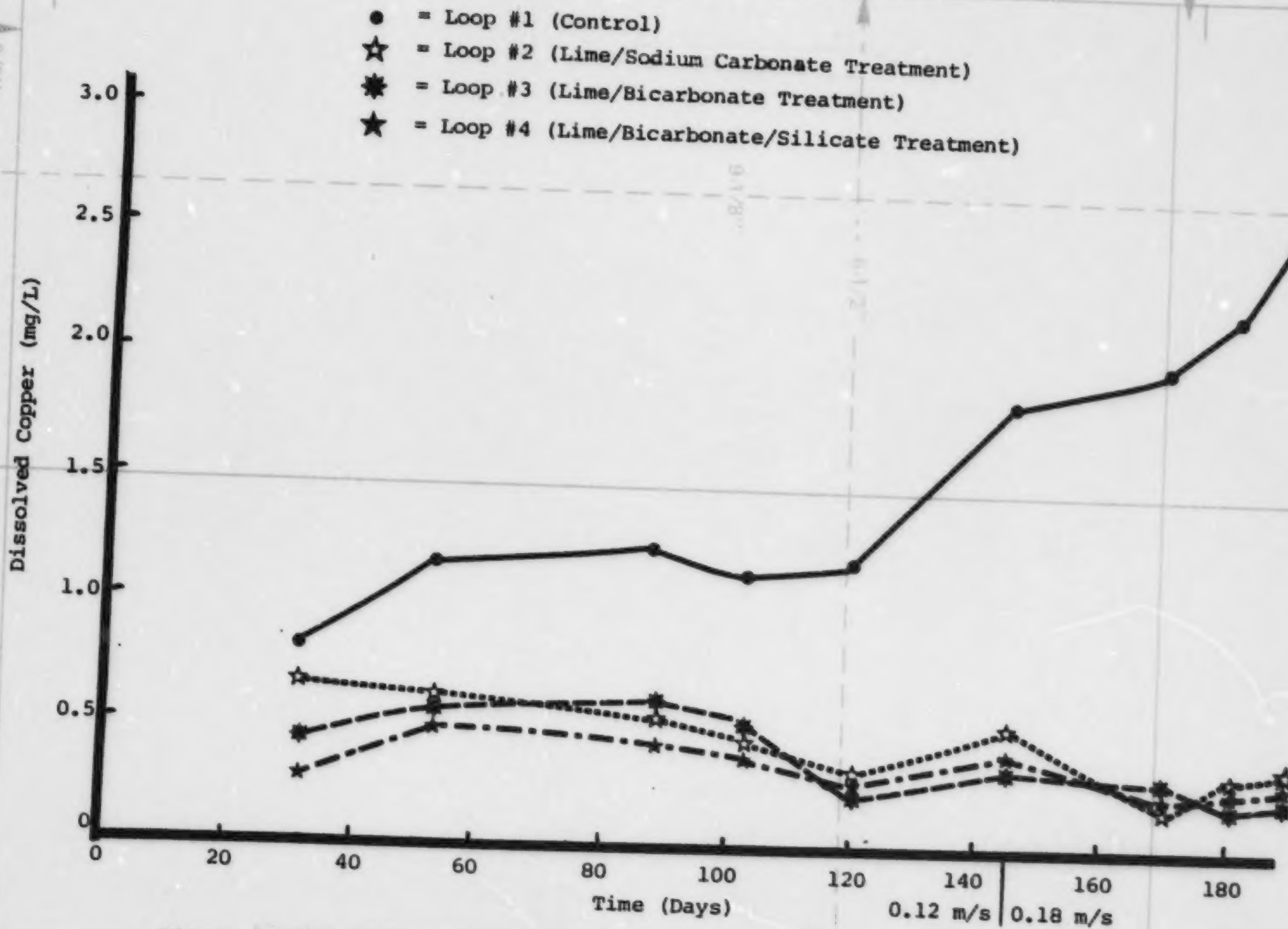

Figure 7. Tolt pilot plant test results - copper leaching from copper piping.

Lead was also found to leach from copper pipe. The results of this analysis are presented in Table 12. To determine the source of lead, a section of unused 1/4" tubing, utilized to construct the test units, was dissolved in nitric acid and analyzed for lead by flame A.A.S. with background correction. In this one test, lead was found to make up .0055% of the copper pipe.

ASTM alloy specifications (B42-80) for copper pipes make no specification for lead content, only copper and phosphorus. In copper used for other applications, as much as .004% lead is permitted. Copper pipe manufacturers have indicated that the type of copper tubing which was used for this test is commonly manufactured from recycled copper products and this practice may result in the introduction of lead impurities to the pipe. This suggests that a survey of lead in various brands and lots of copper piping may be necessary to determine whether this is a significant source of lead in drinking water.

Copper Pipe and 50/50 Lead/Tin Solder

Copper and lead leaching from copper pipe with 50/50 lead/tin solder was analyzed and is presented in Figures 8 and 9. Average % reductions in dissolved lead and copper are presented in Table 13. Tin leaching was also measured but was below the detection limit of 100 µg/L.

Copper leaching was reduced with treatment and generally increased with time in the control loop. Dissolved copper levels were usually lower in the copper plus 50/50 lead/tin leaching loop than in the copper pipe test loop. This is a result of the sacrificial corrosion of the solder when placed in contact with the more noble copper.

Dissolved lead levels generally were initially quite high and decreased with time. Lead levels were lower in the treated water loops than in the control loop for the first part of the tests, but after approximately 120 days, the control loop showed lower lead levels than the treatment loop. This phenomena is due to the depletion of lead near the surface of the solder and the subsequent formation of a tin oxide film which protects the solder from further corrosion. This phenomena is discussed in detail later in this Section and in Volume III of the Seattle Distribution System Corrosion Control Study.[9]

TABLE 13. AVERAGE % REDUCTION IN METAL LEACHING RESULTS FROM COPPER PIPE PLUS 50/50 Pb-Sn SOLDER

Treatment	Dissolved Pb	Dissolved Cu
Control	0	0
Lime/Sodium Carbonate	80	77
Lime/Bicarbonate	55	78
Lime/Bicarbonate/Silicate	70	81

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TABLE 12 LEAD LEACHING RESULTS FROM COPPER PIPE

Treatment	Days Exposure	Lead (µg/L)	Average	% Reduction
Control	34	9.5	8.2	0
	53	21.0		
	87	26.5		
	101	2.5		
	120	6.5		
	145	1.0		
	171	2.0		
	180	2.5		
	188	2.5		
Lime/Soda Ash	34	9.5	2.8	66%
	53	2.0		
	87	47.5*		
	101	3.5		
	120	2.5		
	145	2.0		
	171	<1.0		
	180	1.0		
	188	2.0		
Lime/Bicarbonate	34	17.0	5.1	38%
	53	10.0		
	87	77.5*		
	101	3.5		
	120	1.0		
	145	2.0		
	171	3.0		
	180	2.5		
	188	1.5		
Lime/Bicarbonate/ Silicate	34	12.5	3.9	52%
	53	4.0		
	87	9.5*		
	101	4.0		
	120	1.5		
	145	3.5		
	171	1.5		
	180	3.0		
	188	1.0		

*Data points not included in calculations because of treatment breakdown prior to tests.

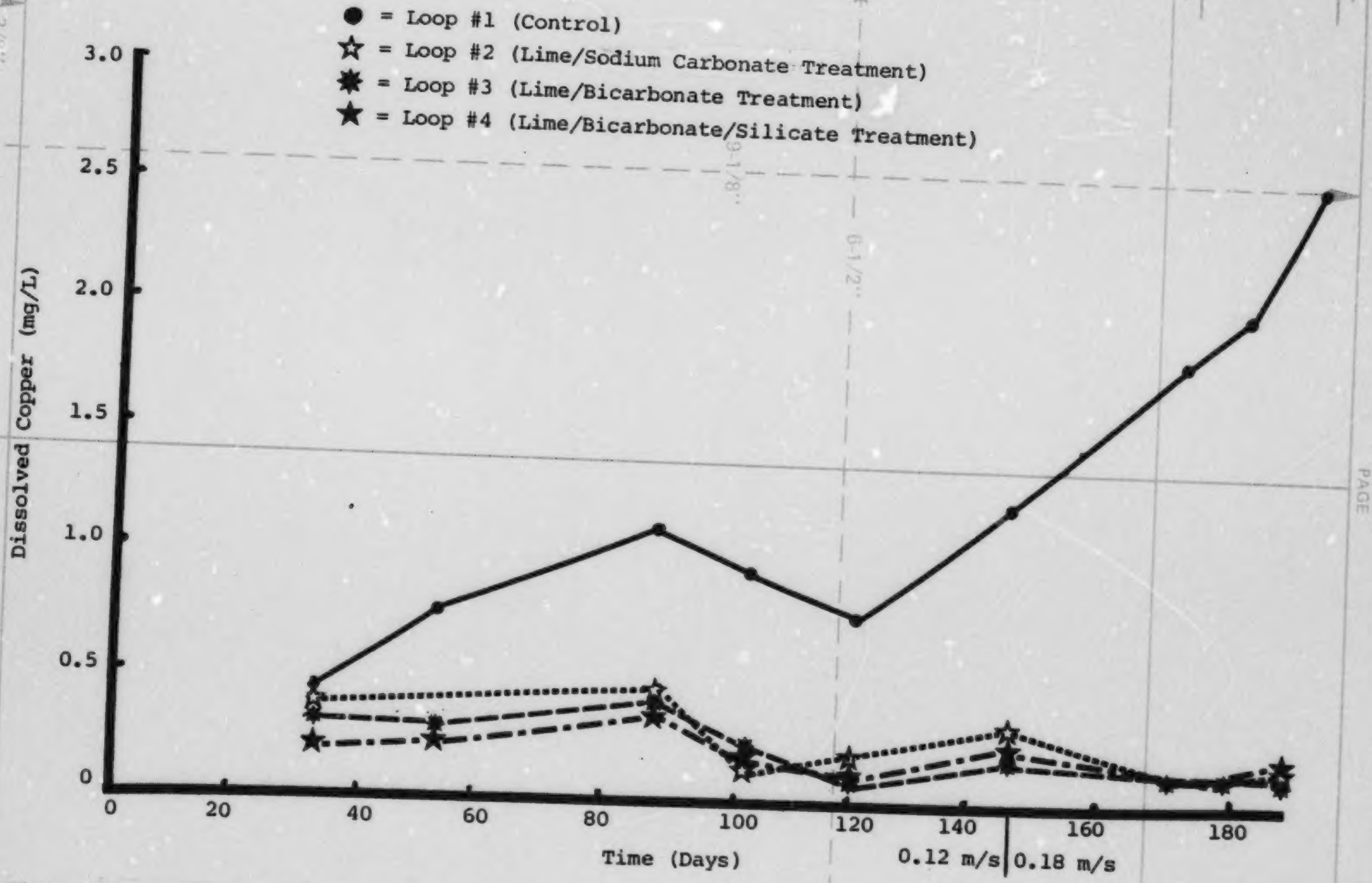

Figure 8. Tolt pilot plant test results - copper leaching from copper piping and 50/50 lead/tin solder.

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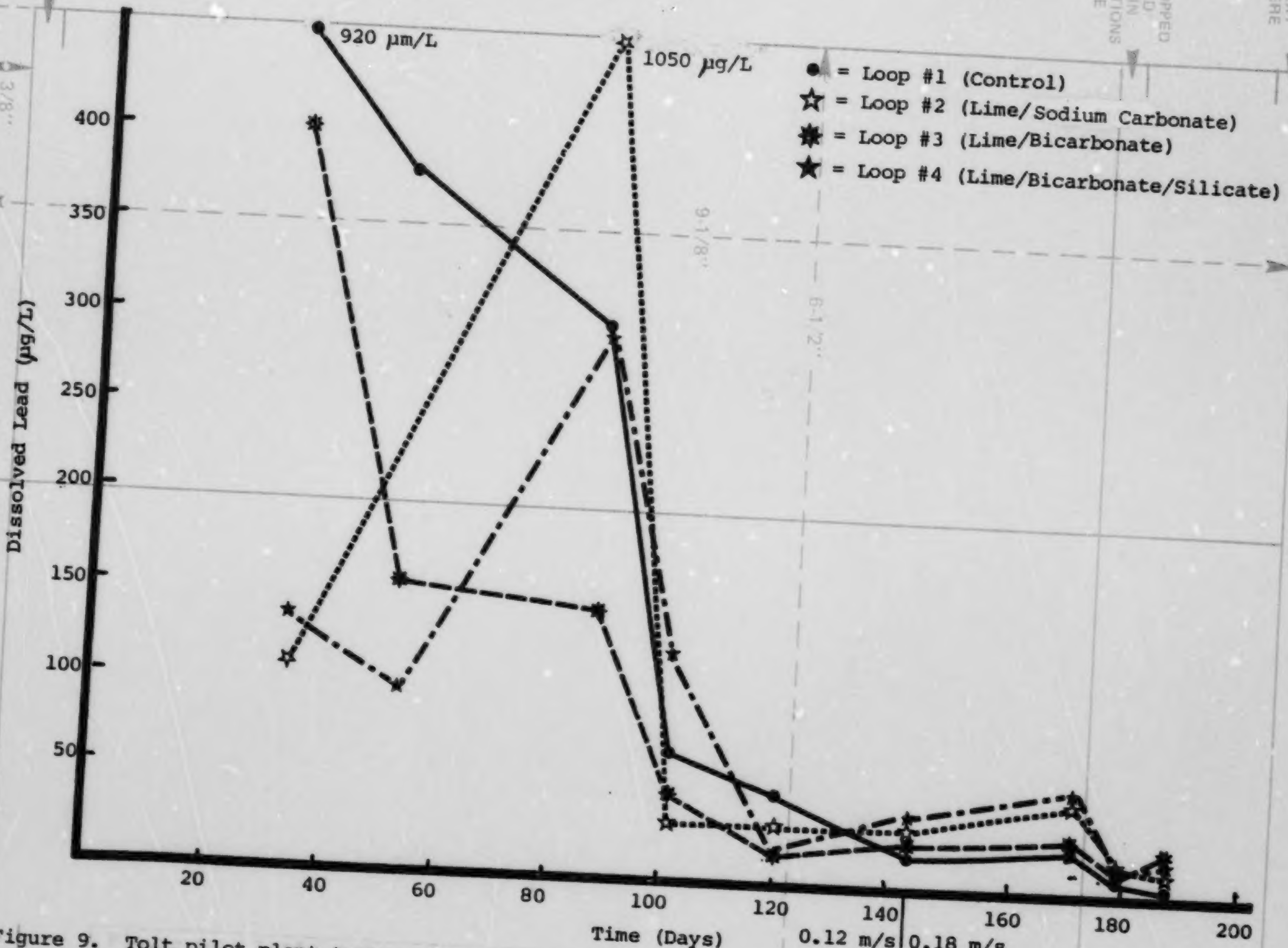

Figure 9. Tolt pilot plant test results - lead leaching from copper piping and 50/50 lead/tin solder.

The high lead levels which occurred at 87 days were the result of treatment breakdown. Approximately 7 to 12 hours before the beginning of the metal leaching tests, the chemical feed pumps failed, resulting in the treatment loops exposure to untreated water. This apparently caused a disruption in the protective film with high lead leaching as a result.

Copper Pipe and 95/5 Tin/Antimony Solder

Copper and lead leaching from copper pipe plus 95/5 tin/antimony solder was analyzed and is presented in Figure 10 and Table 14. Average % reductions in dissolved lead and copper are presented in Table 15. Dissolved tin and antimony were also measured but both were under the detection limit of 100 µg/L and 1.4 µg/L, respectively.

Lead was found to initially leach from the tin/antimony solder, as demonstrated in Table 14. However, after approximately 74 days, lead levels were near or below the detection limit. Table 14 also shows that treatment significantly reduced lead leaching from the solder during the initial lead leaching period. Also, a spike occurred on Loop #2 when there was a breakdown in treatment. This is probably due to the deterioration of the corrosion film during changing water qualities.

Figure 10 illustrates that, as in the previously mentioned metal leaching tests, copper leaching was reduced with treatment and generally increased with time. Copper leaching was initially lower in the copper pipe than in the copper plus 95/5 tin/antimony solder because of the sacrificial corrosion of the solder. With time, however, copper leaching became approximately equal in the two leaching sections. This is due to the formation of a passivation film on the solder which inhibits sacrificial corrosion.

Galvanized Steel Pipe

Water from galvanized pipe metal leaching loops was analyzed for zinc, lead and cadmium. The results are presented in Figures 11 through 13.

Table 16 shows that the treatments reduced the amount of zinc leaching and increased cadmium and lead leaching.

Figure 11 demonstrates that lime/sodium carbonate treatment gave better zinc leaching reduction results than both lime/bicarbonate and lime/bicarbonate/silicate treatment. Again, the flow increase from 0.12 to 0.18 m/s resulted in greater increases in zinc leaching in the control loop than in the treatment loops.

All the treatments, however, increased lead and cadmium leaching. The increases in cadmium and lead dissolution from galvanized steel pipe are not understood.

TABLE 14. LEAD LEACHING FROM COPPER PIPE PLUS 95/5 TIN/ANTIMONY SOLDER

	Lead, µg/L			
Exposure (days)	Control	Lime/ Sodium Carbonate Treatment	Lime/ Bicarbonate Treatment	Lime/ Bicarbonate/ Silicate Treatment
26	113	65	4	1.5
45	17	3	11	<1
79	<1	35*	<1	<1
93	1.5	2.5	<1	<1
112	2	<1	<1	<1
137	<1	<1	<1	<1
163	<1	NA	<1	<1
172	<1	<1	<1	<1
180	1½	<1	<1	<1

NA = Not analyzed.
*Treatment breakdown.

TABLE 15. AVERAGE % REDUCTION IN METAL LEACHING FROM COPPER PIPE PLUS 95/5 TIN/ANTIMONY SOLDER

Treatment	Dissolved Pb	Dissolved Cu
Control	0	0
Lime/Sodium Carbonate	48	55
Lime/Bicarbonate	89	66
Lime/Bicarbonate/Silicate	99	72

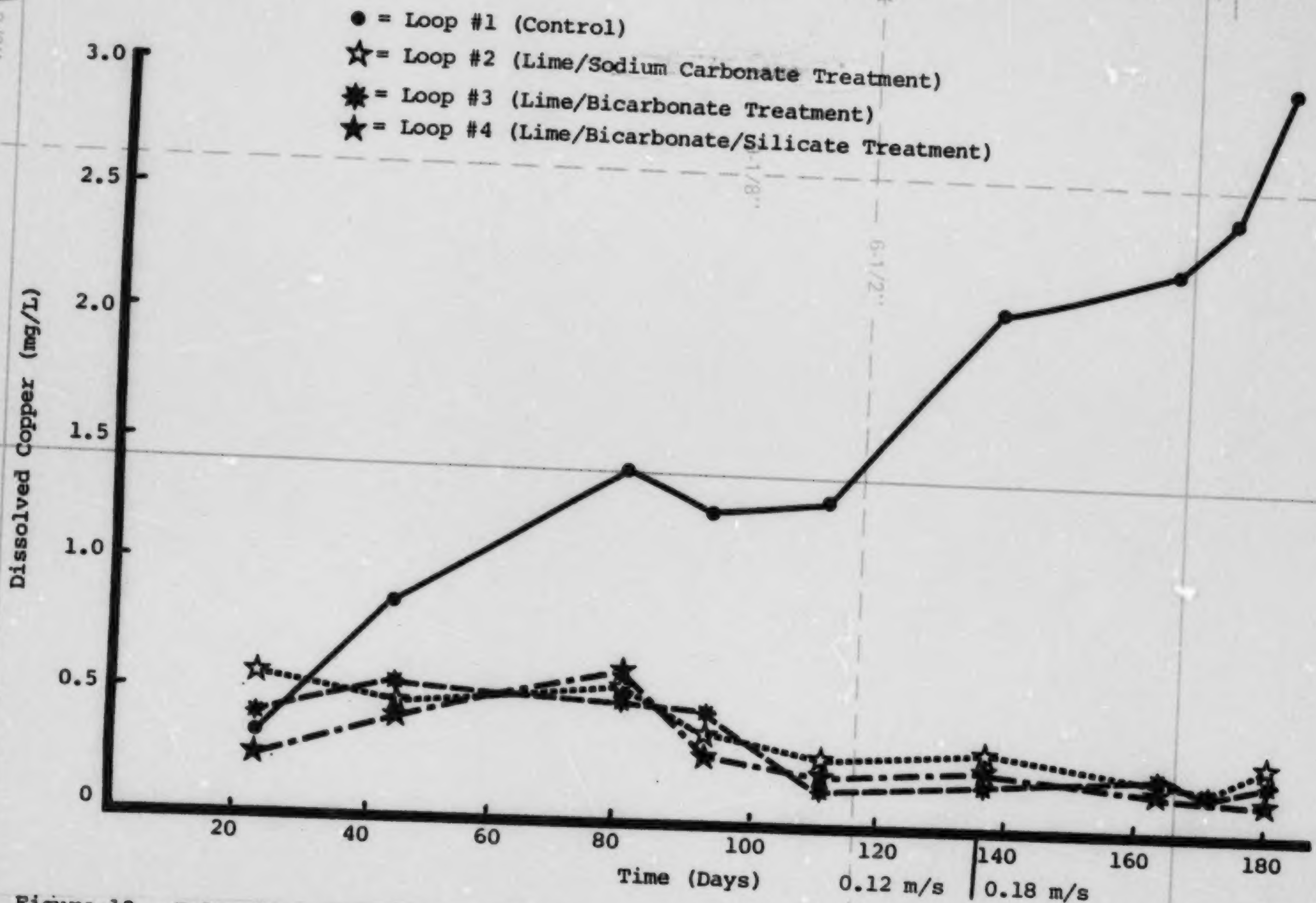

Figure 10. Tolt pilot plant test results - copper leaching from copper piping and 95/5 tin/antimony solder.

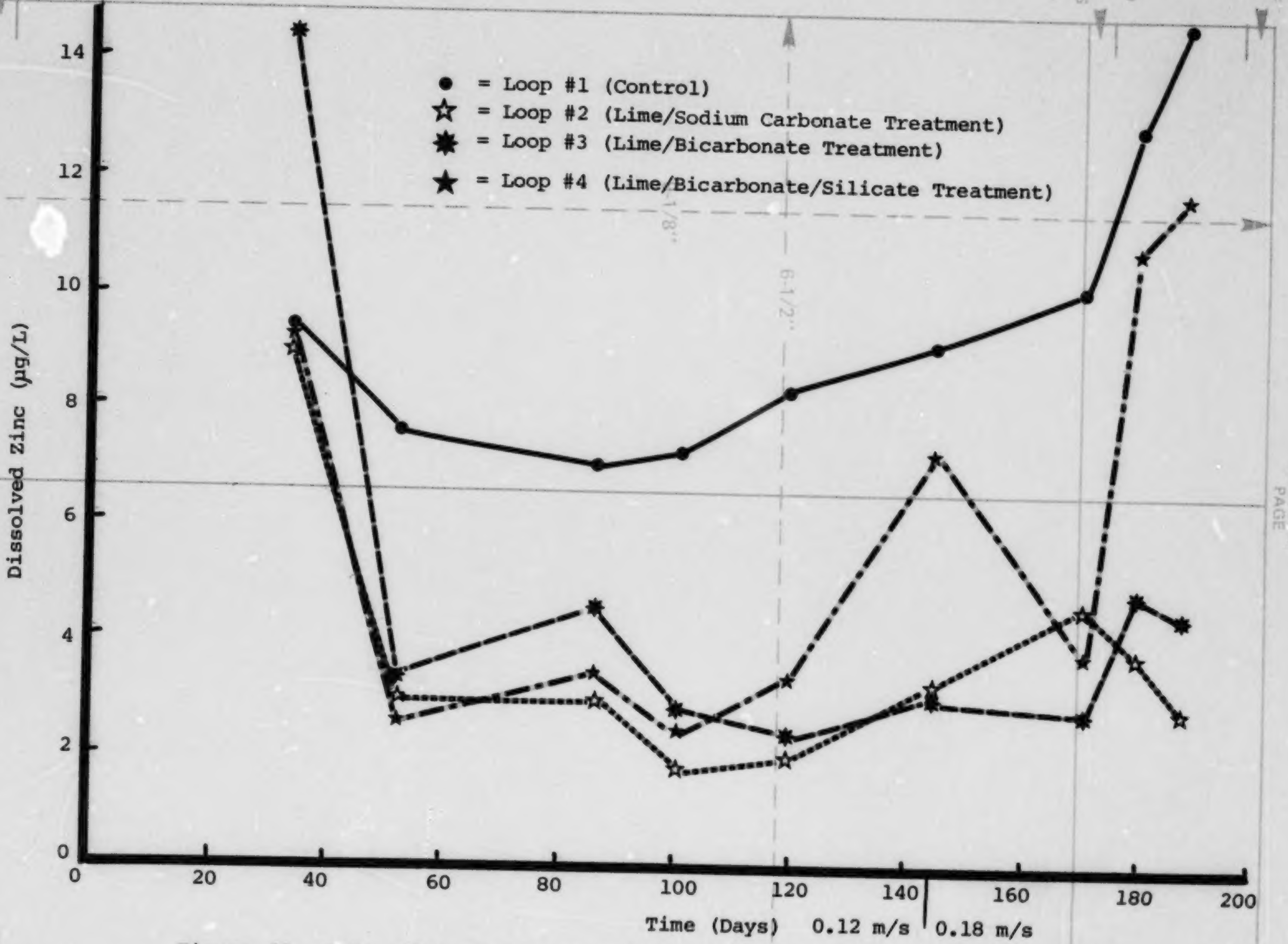

Figure 11. Tolt pilot plant test results - zinc leaching from galvanized piping.

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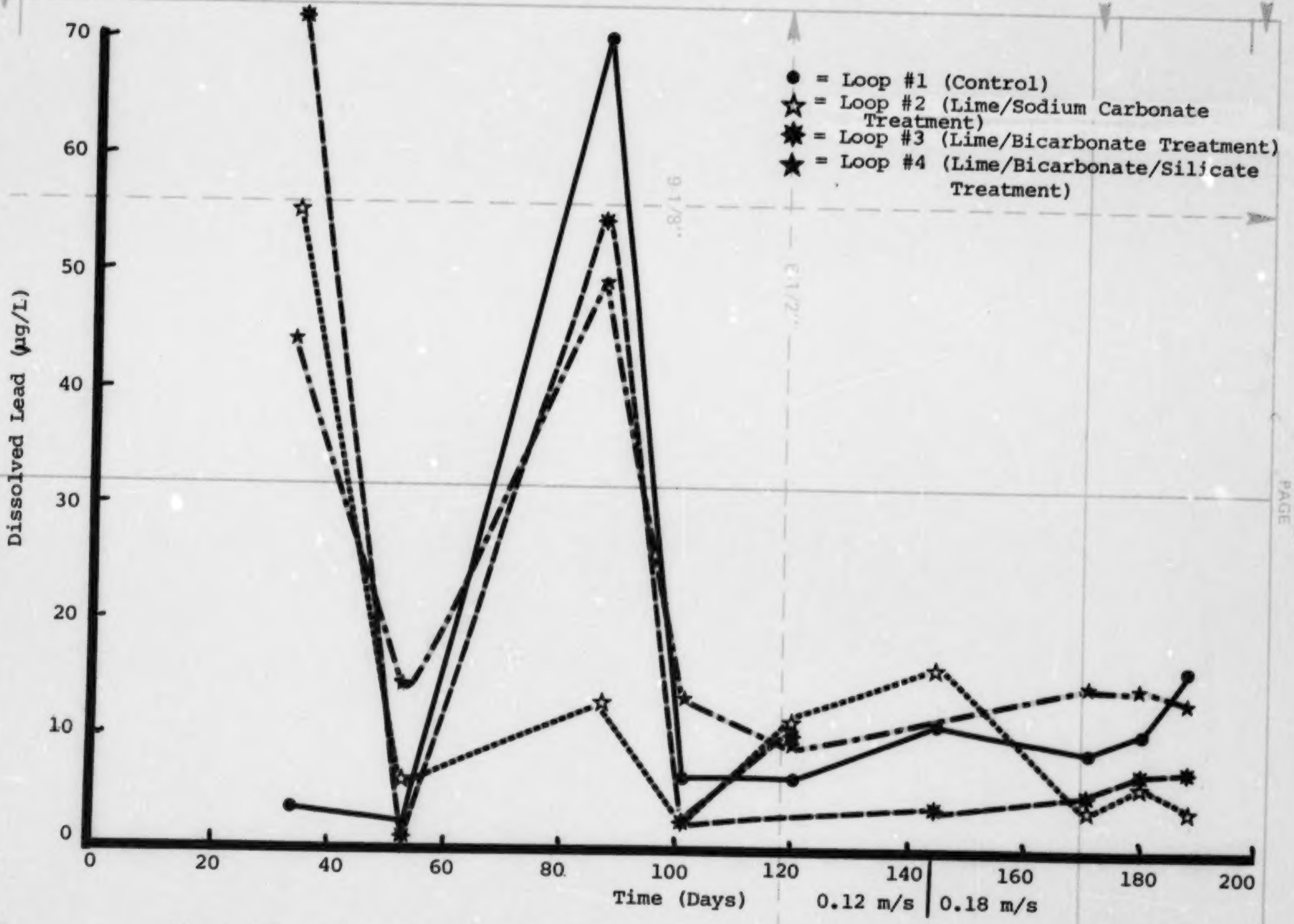

Figure 12. Tolt pilot palnt test results - lead leaching from galvanized piping.

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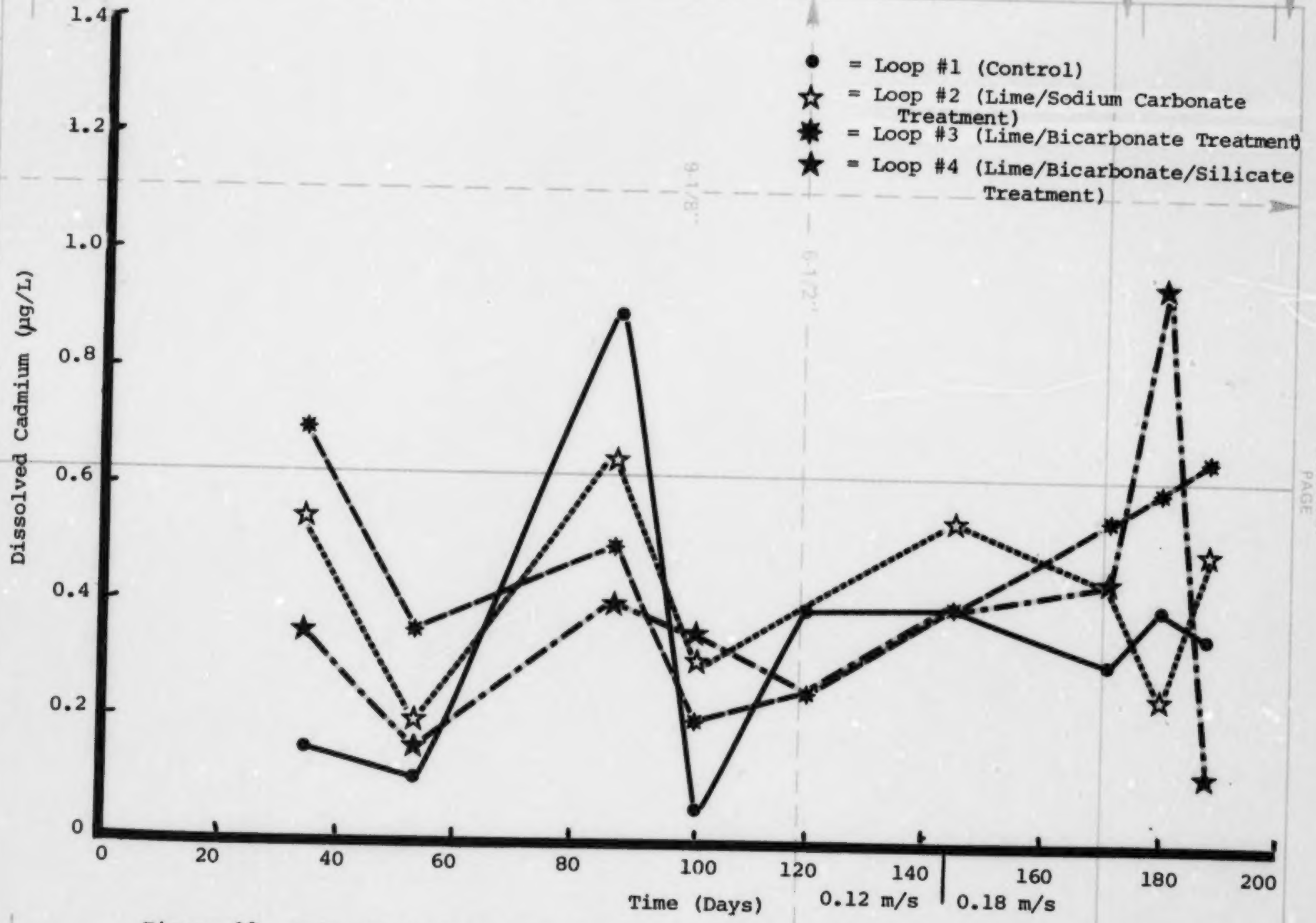

Figure 13. Tolt pilot plant test results - cadmium leaching from galvanized piping.

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TABLE 16. AVERAGE % REDUCTION IN METAL LEACHING RESULTS FROM GALVANIZED STEEL PIPE

Treatment	Zn	Pb	Cd
Control	0	0	0
Lime/Sodium Carbonate	61	-105	-35
Lime/Bicarbonate	51	-128	-35
Lime/Bicarbonate/Silicate	38	-112	-47

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ANALYSIS OF CORROSION FILMS

General

Corrosion films on the metal leaching test pipe loops were analyzed by SEM and EDAX. Small pieces were removed from the copper and galvanized steel test pipes following the 0.12 m/s and the 0.18 m/s velocity test period. In addition, films formed on the 50/50 Pb-Sn and 95/5 Sn-Sb solders were also analyzed following the 0.18 m/s velocity test period. All SEM and EDAX photographs are presented in Appendix E.

Copper Pipe

Control Loop --

The SEM and EDAX analysis for the copper control loop are presented in Figures E-1 through E-6. Figures E-1 and E-2 demonstrate that at the 0.12 m/s velocity, a very thin copper film is present with other surface deposits. The darker areas, which can be seen in both these figures, are small pits in which the bare metal is exposed to the solution. The presence of these pits is a common characteristic of copper corrosion in Tolt water. The EDAX analysis (Figure E-3) shows that the composition of the surface films is mostly copper, with surface deposits of both silica and iron. The source of the silica deposits is from the naturally occurring silicate in Tolt water, while the iron is a result of the deposition of iron corrosion products from the upstream ISWS and metal leaching test loops.

At the 0.18 m/s velocity, a heavy concentration appears on the pipe surface (Figures E-4 and E-5). This surface film is much different than that which was formed at the 0.12 m/s velocity. Figure E-6 shows that the composition of the film is a mixture of copper and iron. Apparently, the iron corrosion products from the upstream ISWS and metal leaching test loop built up on the copper test section. Although this did not reduce copper leaching from the pipe section, it did result in a corrosion film that is not like the films found in premise plumbing systems. For this reason, in future tests all galvanized steel and iron parts of the ISWS test unit should be replaced with plastic parts and iron pipe should be eliminated from the metal leaching test loop.

Lime/Sodium Carbonate Treatment --

The SEM and EDAX analyses for the lime/sodium carbonate treatment are presented in Figures E-7 through E-13. At 0.12 m/s, a thin copper film is present with much more surface deposits than in the control loop (Figures E-7 and E-8). Absent from this test loop are the numerous small pits which were evident in the control loop. There were, however, some small pits which formed in an area where the surface film appears to have been removed. This is shown in Figure E-7 and at a greater magnification in Figure E-9.

The EDAX analysis for the lime/sodium carbonate test loop (Figure E-10) shows that, as in the control loop, the film is composed mainly of copper, with surface deposits of silica and iron.

Figures E-11 and E-12 demonstrate that at 0.18 m/s, there are considerably less surface deposits than at the 0.12 m/s velocity. The EDAX analysis presented in Figure E-13 shows that the surface film is composed mainly of copper, with small deposits of iron and silica. Also, the film has the appearance of a typical copper film as predicted by the Duplex copper film model.[13] This model predicts the formation of a two-layer copper oxide film which grows from the metal surface outward. As the film continues to grow, the outer layer becomes insulated from the metal and peels off or dissolves. This double layer and peeling effect can be seen clearly in Figure E-12.

Lime/Bicarbonate Treatment --

Analysis of the films formed on the lime/bicarbonate treatment copper test loop are presented in Figures E-14 through E-20. At 0.12 m/s, Figure E-14 shows a typical copper film as predicted by the Duplex copper film model.[13] At higher magnification, the double layer and peeling effect of the film clearly is evident (Figure E-15). Again, the numerous small pits which occurred on the control loop were absent; however, as demonstrated in Figure E-16, small pits did occur where the film had been removed by the corrosion/erosion process. Figure E-17 demonstrates that the film is composed mostly of copper.

Figures E-18 through E-20 show that the velocity increase had virtually no effect on the appearance of composition of the film. Again, the Duplex-type film is present and is composed of copper with small amounts of iron and silica.

Lime/Bicarbonate/Silicate Treatment --

The SEM and EDAX analyses for lime/bicarbonate/silicate treatment are presented in Figures E-21 through E-26. Figures E-21 and E-22 show that at 0.12 m/s, a thin double layer copper film was formed, with a thick silicate deposit which partially covered the surface. The composition of the film is presented in Figure E-23 and shows high concentration of copper and silica with some iron present.

At the 0.18 m/s velocity, there are fewer and thinner silicate deposits on the surface than at 0.12 m/s (Figures E-24 through E-26). This indicates that protection afforded by silicate films is very unlikely due to its irregularity and at higher velocities, the silicate deposits can be scoured off the surface of the pipe.

Galvanized Steel Pipe

Control Loop --

The SEM and EDAX analyses for the galvanized steel pipe exposed to untreated Tolt water are presented in Figures E-27 through E-35. Figure E-27 demonstrates that at 0.12 m/s, a corrosion film is absent and several pits have formed. In fact, as shown in Figure E-28, one pit appears to be completely through the zinc layer, exposing the underlying iron. The EDAX analysis also demonstrates that iron is exposed along with smaller quantities of aluminum, silica and lead (Figure E-29). The aluminum and lead are most likely impurities contained in the galvanizing, while the silica is derived from naturally occurring silicate in Tolt water.

At the 0.18 m/s velocity, Figures E-30 and E-31 show that although no distinct pits are present, a great deal of the surface has been severely corroded. The EDAX analysis shows that in the corroded areas, relatively large amounts of iron, aluminum, copper and lead are present (Figure E-32).

Presented in Figures E-33 through E-35 are uniformly sized spheres which were observed on the surface of several of the galvanized steel pipe test sections. The spheres are each approximately 15 microns in diameter and are composed of iron (Figure E-35). The nature and source of these spheres is unknown.

Lime/Sodium Carbonate Treatment --
The SEM and EDAX analyses for the lime/sodium carbonate treatment are presented in Figures E-36 through E-40. Figure E-36 shows that a distinct corrosion film was deposited at 0.12 m/s. The film appears to cover the entire surface with no pits present. The elemental composition of the film, presented in Figure E-37, is mainly zinc with smaller quantities of both iron and silica.

At 0.18 m/s, most of the surface film appears to have been removed, thereby exposing the galvanized layer to the solution (Figures E-38 and E-39). The EDAX analysis presented in Figure E-40 further emphasizes this point. Small quantities of aluminum and lead are present at the surface as was the case with the control loop. In contrast to the control loop, however, very little iron is present.

Lime/Sodium Bicarbonate Treatment --
The SEM and EDAX analyses for the lime/sodium bicarbonate treatment loop are presented in Figures E-41 through E-45. Figure E-41 demonstrates that with this treatment a thick porous film was deposited at 0.12 m/s which covered the entire surface area. The film is much thicker than the film formed under the lime/sodium carbonate treatment. This may be in part due to the lower pH ranges which occurred with the lime/sodium carbonate treatment. The composition of the film presented in Figure E-42 is mainly zinc with small amounts of iron silica and aluminum present.

Figures E-43 and E-44 show that at 0.18 m/s, a surface film is not as thick as the film formed at 0.12 m/s, but still approximately covers the entire surface area. The composition of the film is nearly identical to that formed under the 0.12 m/s velocity. Again, it is comprised mostly of zinc with small quantities of iron, aluminum, silica and calcium (Figure E-45).

Lime/Bicarbonate/Silicate Treatment --
The SEM and EDAX analyses for the lime/bicarbonate/silicate treatment loop are presented in Figures E-46 through E-50. A very thick porous film which covered most of the surface was formed with this treatment at the 0.4 m/s velocity (Figure E-46). The film was both similar in appearance and composition to the film formed with lime/bicarbonate treatment. Figure E-47 demonstrates that the film was comprised of zinc, silica and iron.

At 0.18 m/s, the film is not as thick as at 0.12 m/s, but the film still covers most of the surface area (Figures E-48 and E-49). The composition of the film is again zinc, silica and iron (Figure E-50).

50/50 Lead/Tin Solder

Control Loop --

The SEM and EDAX analyses for the control loop are presented in Figures E-51 and E-52. The film formed under the control conditions is thin, but appears to be tightly adherent to the solder surface (Figure E-51). The EDAX analysis shows that the major component of the film is tin, with quantities of iron, silica and lead present.

Initially, the small amount of lead measured in the EDAX analysis was very surprising since lead accounts for 50% of the solder by weight. However, when the SEM and EDAX analyses results are considered along with the lead leaching test results (Figure 9), this apparent anomaly becomes clear. Because of the low pH in the control loop, lead readily dissolves and the high level of lead leaching during the first few months of the leaching test depleted the lead near the surface of the solder. The depletion of lead from the solder then allowed an insoluble tin oxide passivation film to form on the solder surface.

The depletion of lead and the formation of a tin passivating film on the solder is not, however, a characteristic of premise plumbing corrosion. Residential tap monitoring in Seattle has shown that lead continues to leach from lead/tin soldered copper plumbing for many years after construction. This indicates that the solder is not depleted of lead or passivated by a tin film under the changing flow conditions of a premise plumbing system. It may therefore be necessary to include on-off cycling in future metal leaching tests to better simulate actual premise plumbing conditions.

Lime/Sodium Carbonate Treatment --

The SEM and EDAX analyses for the lime/sodium carbonate treatment loop are presented in Figures E-53 and E-54. The film formed under this treatment condition has a different physical appearance than the film formed under the control condition. Figure E-53 illustrates that this is a thin, loosely adherent corrosion film. In contrast to the control loop, Figure E-54 demonstrates that the major component of the treatment loop corrosion film is lead, with some iron, tin, silica and copper present. Lead is not depleted in the treatment loop because of the higher pH, but forms a lead oxide or lead carbonate film on the surface of the solder.

This lead film can, however, dissolve and release large quantities of lead into the drinking water if the pH conditions change suddenly. This is evidenced by the spikes which occurred following the treatment breakdown in the metal leaching tests (Figure 9). To avoid this type of situation during full-scale treatment, it is crucial to avoid treatment breakdowns and maintain a stable high pH.

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Lime/Sodium Bicarbonate Treatment --

The SEM and EDAX analyses for the lime/sodium bicarbonate treatment loop are presented in Figures E-55 and E-56. The film formed under this treatment condition was very similar to that formed under the lime/sodium carbonate treatment. As shown in Figure E-55, the film was thin and loosely adherent. Again, the composition of the film is mainly lead, with iron, silica and tin also present (Figure E-56). Therefore, the same conclusion presented under the lime/sodium carbonate treatment section also applies to the lime/sodium bicarbonate treatment.

Lime/Bicarbonate/Silicate Treatment --

The SEM and EDAX analyses for the lime/bicarbonate/silicate treatment are presented in Figures E-57 and E-58. The film shown in Figure E-57 is similar to the other treatment loops in that it is thin and loosely adherent. With this treatment, however, the film is partially covered with silicate deposits. This is evidenced by the EDAX analysis in Figure E-58, which shows lead to be the main constituant of the film, with large amounts of silica present. Also contained in the film are tin and iron.

Tin/Antimony Solder

SEM and EDAX analyses were also performed on the tin/antimony leaching test loop after 180 days exposure. Figures E-59 through E-62 demonstrate that the physical appearance of the film is not changed by increasing pH. In addition, the composition of the film is not significantly changed by treatment. The EDAX analysis presented in Figures E-63 through E-66 show that the main component of the film is tin, with trace quantities of silica, copper and iron. The silica content of lime/bicarbonate/silicate treatment loop corrosion film was somewhat greater than the control and the other treatment loops.

The similar characteristics of the corrosion film under control and treatment conditions, as analyzed with SEM and EDAX, agree well with the low metals concentrations observed in the metal leaching test. It can be concluded that because of the protective nature of the tin film formed under both control and treatment conditions, metal leaching from tin/antimony solder will be minimal.

COMPOSITE EVALUATION

General

A composite evaluation of treatment alternatives was performed to determine the most feasible and effective corrosion treatment for the Tolt river supply. The evaluation was based on ISWS and metal leaching tests presented in the previous sections, cost of treatment, ease of handling, and reliability of treatment. Each evaluation criteria is explained in Table 17. More points were awarded for reduction of copper corrosion than for galvanized or steel corrosion because Seattle's long-term corrosion control strategy is aimed at discouraging the use of galvanized and steel piping for private domestic plumbing. Similarly, lead leaching is a greater concern than the

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other metals and more points were given for it.

Results

The composite evaluation of treatment alternatives is presented in Table 18. The overall best treatment is the lime/sodium carbonate treatment. Lime/bicarbonate and lime/bicarbonate/silicate treatments ranked a close second and third, while the no treatment alterantive ranked last.

The three treatment alternatives ranked very close to each other. Lime/sodium carbonate treatment and lime/sodium bicarbonate treatment ranked approximately equal in the coupon tests and metal leaching evaluation criteria; however, the lime/sodium carbonate treatment was judged better because of lower costs and because a constant pH can be maintained with either lime or sodium carbonate feed in the event of an equipment breakdown of one feed system. The lime/bicarbonate/silicate treatment was ranked higher than the other treatments in the coupon tests and metal leaching test evaluation criteria. It did not prove to be the best alternative because of the added capital investment, chemical costs and maintenance requirements of an additional feed system.

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TABLE 17. CHEMICAL TREATMENT EVALUATION CRITERIA

Evaluation Criteria	Maximum Points	Description
COUPON TESTS	40	Points Awarded = (% Reduction in Coupon Weight Loss)(Maximum Points)
a. Copper Weight Loss	20	
b. Galvanized Steel Weight Loss	10	
c. Iron Weight Loss	5	
d. Iron Pitting	5	
METAL LEACHING TESTS	40	Points Awarded = (% Reduction in Lead Leaching)(Maximum Points)
a. Lead Leaching from:		
- 50/50 Pb/Sn Solder/Cu	10	
- Galvanized Steel Pipe	8	
- 95/5 Sn/Sb Solder/Cu	2	
- Copper Pipe	2	
b. Copper Leaching from:		Points Awarded = (% Reduction in Copper Leaching)(Maximum Points)
- Copper Pipe	6	
- Copper Pipe with 95/5 Sn/Sb Solder	1	
- Copper Pipe with 50/50 Pb/Sn Solder	1	
c. Zinc Leaching from Galvanized Steel Pipe	6	Points Awarded = (% Reduction in Zinc Leaching)(Maximum Points)
d. Cadmium Leaching from Galvanized Steel Pipe	4	Points Awarded = (% Reduction in Cadmium Leaching)(Maximum Points)
CHEMICAL COSTS / CAPITAL COSTS	5	Chemical costs were evaluated as present worth values expressed as equivalent uniform annual costs. If the costs were high, the alternative was given a low rating score.
EASE OF HANDLING	5	If chemicals are difficult to handle, the alternative was given a low rating score.
RELIABILITY / EQUIPMENT MAINTENANCE	10	If the treatment can provide a year-round supply of constant quality water with a minimum of treatment breakdown, the alternative was given a high rating score. If a high pH cannot be maintained with either treatment chemical alone, the alternative was given a low ranking score.

TABLE 18. COMPOSITE EVALUATION OF TREATMENT ALTERNATIVES

Evaluation Criteria	Maximum Points	No Treatment	Loop #2	Loop #3	Loop #4
COUPON TESTS	40				
a. Copper Weight Loss	20	0	17.0	17.0	16.6
b. Zinc Weight Loss	10	0	2.4	4.3	4.9
c. Iron Weight Loss	5	1.2	0	0.5	1.5
d. Iron Pitting	5	0.9	0.4	0.9	0
METAL LEACHING TESTS	40				
a. Lead Leaching:					
- 50/50	10	0	7.8	5.5	6.9
- Galvanized	8	4.5	0.8	0	0.5
- 95/5	2	0	1.0	1.8	2.0
- Copper	2	0	1.3	0.8	1.0
b. Copper Leaching:					
- Copper	6	0	4.1	4.4	4.7
- 95/5	1	0	0.6	0.7	0.7
- 50/50	1	0	0.8	0.8	0.8
c. Zinc Leaching	6	0	3.7	3.1	2.3
d. Cadmium Leaching	2	0.6	0.2	0.2	0
COSTS OF CHEMICALS	5	5	4	2	1
EASE OF HANDLING	5	5	2	2	1
RELIABILITY/MAINTENANCE	10	10	5	4	3
TOTAL	100	27.2	51.1	48.0	46.9

SECTION 7

BENEFITS OF TREATMENT

GENERAL

The treatment of Tolt water with lime/sodium carbonate, lime/sodium bicarbonate, or lime/bicarbonate/silicate, is expected to have a positive impact on the customer by means of improved water quality at the tap, aesthetic improvements, and economic benefits.

As demonstrated in the composite evaluation, lime/sodium carbonate treatment proved to be the best overall treatment for the Tolt supply.

A savings of $456,000 is realized by feeding sodium carbonate instead of sodium bicarbonate and eliminating silicate treatment. Chemical costs are presented in Table 19. Using cost information from Table 4 and usage data from Table 5 it can be shown that the decrease in lime dosage will result in an additional savings of about $20,000.

BENEFITS OF TREATMENT

Changes in Water Quality

Lime/sodium carbonate treatment will raise the pH and alkalinity, thereby reducing the corrosiveness of Tolt water. As a result, copper, zinc, and lead levels in overnight standing tap water will be substantially reduced. Also expected is a reduction in the percentage of samples which exceed the MCL for these metals. Small or no reductions of cadmium and iron levels in overnight standing water are expected. A higher percentage of residential samples exceeding the cadmium MCL is not anticipated because the present levels are only about 1/10 of the MCL.

TABLE 19. CHEMICAL COSTS PER YEAR*

Chemical	Dosages, mg/L	Amount per year
Sodium Bicarbonate	20	$460,000
Silicate	4.0	$131,000
Sodium Carbonate	9.0	$135,000

*Based on cost of chemicals delivered at Tolt Regulating Basin, June 1981.

It has also been documented that treatment will decrease asbestos leaching from asbestos cement pipe.[4]

Aesthetic Impact

Complaints of red water and metallic taste and odor should decrease following treatment. The customer will also benefit from the reduction of red and blue fixture and clothing stains caused by the corrosion of galvanized and copper pipe.

Economic Benefits

The expected percent reductions in corrosion rates resulting from lime treatment are expected to significantly increase the service life of premise plumbing in the Tolt service area. Copper pipe service life is expected to increase by approximately 600%. Galvanized steel pipe service life is also expected to increase, but the amount of increase is uncertain. The longer service life means a reduction in plumbing replacement and maintenance costs. Additional cost savings are expected for (1) distribution system maintenance cost, and (2) costs associated with responding to corrosion-related water quality complaints within the City of Seattle and the suburban water agencies. A detailed analysis of the economic benefits of treatment can be found in the Seattle Internal Corrosion Study.[4]

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APPENDIX A

TOLT pH STABILITY TESTS

OBJECTIVES

The objectives of these bench tests were to simulate the maximum pH depression that would occur in the Tolt distribution system with several combinations of corrosion control treatments. The tests were designed to estimate reasonable average target pH values for the flow-through pilot tests.

PROCEDURE

A 3.8 L sample of Tolt pipeline water (treated with chlorine and fluoride) was collected (5/3/78) and analyzed for pH and alkalinity. The CO_2 level was also calculated. 800 mL aliquots were treated with lime/sodium carbonate, lime/sodium bicarbonate, sodium carbonate/sodium silicate, lime/sodium bicarbonate; sodium silicate close to the 0.00 CO_2 point. The five aliquots, including a control, were stirred on a jar test apparatus at 12 RPM for 17 hours and allowed to stand still for another 21 hours. pH readings were taken at four time intervals. Further pH depression following a 0.4 mg/L chlorine dosage was calculated.

RESULTS

The results are presented in Tables A-1 and A-2.

CONCLUSIONS

Pilot testing should compare lime/sodium carbonate (minimum alkalinity and minimum distribution pH) against lime/sodium bicarbonate (maximum alkalinity, pH) and against lime/sodium bicarbonate/silicate (maximum alkalinity, pH and elevated Tolt distribution silica level).

The flow-through tests comparing lime/sodium carbonate to lime/bicarbonate and lime/bicarbonate/silicate should maintain a 0.1 pH difference to simulate the average differences that would affect pipeline-served customers (0.0 pH difference) and reservoir-served customers (0.2 pH difference). The higher alkalinity treatments should be maintained at a pH of 7.95 as were previous tests performed on treated Cedar water.

TABLE A-1. pH STABILITY TESTS

Treatment	Dosages				Concentrations			pH			
	Ca(OH)2 mg/L	Sodium Carbonate mg/L	Sodium Bicarbonate mg/L	Silicate mg/L	Alkalinity mg/L CaCO3	Na mg/L	Ca mg/L	0 hours pH	14 hours pH 20°C	17 hours pH 20°C	38 hours pH 20°C (no stirring)
Untreated (CO_2 = 7.0 calc.)					2.1	1.05	2.9	5.86	-	-	6.50
Lime/Sodium Carbonate	2.9	8.7			13.5	4.9	4.5	8.05	7.57	7.53	7.55
Sodium Carbonate/Silicate		15.7		5.9	18.1	8.4	-	8.19	7.72	7.64	7.67
Lime/Bicarbonate	4.75		23.		21.7	7.3	5.45	8.02	7.76	7.68	7.78
Lime/Bicarbonate/Silicate	5.7		24.	5.9	25.6	9.05	6.0	8.52	7.86	7.77	7.86

TABLE A-2. EQUILIBRIUM pH VALUES @ 20°C

Treatment	Calculated pH After CO_2 Equilibrium*	Actual Equilibrium pH	Calculated pH After Rechlorination* (.4 mg/L dosage)
Untreated	6.92	6.50	6.61
Lime/Sodium Carbonate	7.72	7.55	7.41
Sodium Carbonate/Silicate	7.85	7.67	7.54
Lime/Bicarbonate	7.93	7.78	7.62
Lime/Bicarbonate/Silicate	8.00	7.86	7.7

$$*\left[H^+\right] = \frac{K_w + K_1\left[H_2CO_3\right] + \sqrt{\left(K_w + K_1\left[H_2CO_3\right]\right)^2 + 8\text{Alk}\,K_1K_2\left[H_2CO_3\right]}}{2\ \text{Alk}}$$

Alk = (2×10^{-5}) (mg/L $CaCO_3$ Alk) $\left[H_2CO_3\right]$ = Atmospheric equilibrium CO_2 conc.

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APPENDIX B

QUALITY CONTROL DATA

TABLE B-1. COUPON QUALITY CONTROL DATA (Summarized by Each Coupon)

Loop No.	Coupon	Days Exposure	Average pH*	pH Range	Average Flow (L/min.)
#1					
Copper	#1	70	5.97	5.40-6.29	9.40
	#2	103	5.94	5.40-6.30	9.43
	#3	131	5.91	5.20-6.30	9.37
	#4	180	5.95	5.20-6.30	9.34
Iron	#1	70	5.97	5.40-6.29	9.40
	#2	131	5.94	5.20-6.30	9.43
	#3	180	5.91	5.20-6.30	9.37
	#4	246	5.95	5.20-6.30	9.34
Galvanized	#1	70	5.97	5.40-6.29	9.40
	#2	131	5.94	5.20-6.30	9.43
	#3	180	5.91	5.20-6.30	9.37
	#4	246	5.95	5.20-6.30	9.34
#2					
Copper	#1	70	7.52	6.10-8.80	9.06
	#2	103	7.63	6.10-8.80	9.09
	#3	131	7.48	6.10-8.80	9.12
	#4	180	7.36	6.10-8.80	9.15
Iron	#1	70	7.52	6.10-8.80	9.06
	#2	131	7.63	6.10-8.80	9.09
	#3	180	7.48	6.10-8.80	9.12
	#4	246	7.36	6.10-8.80	9.15
Galvanized	#1	70	7.52	6.10-8.80	9.06
	#2	131	7.63	6.10-8.80	9.09
	#3	180	7.48	6.10-8.80	9.12
	#4	246	7.36	6.10-8.80	9.15

*Based on daily $[H^+]$ x hrs. exposure, averaged over each coupon's exposure period.

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TABLE B-1. COUPON QUALITY CONTROL DATA (Summarized by Each Coupon), Cont.

	Coupon	Days Exposure	Average pH*	pH Range	Average Flow (L/min.)
#3					
Copper	#1	70	7.68	6.50-8.60	9.49
	#2	103	7.66	6.18-9.40	9.37
	#3	131	7.59	5.94-9.40	9.43
	#4	180	7.62	5.94-9.40	9.43
Iron	#1	70	7.68	6.50-8.60	9.49
	#2	131	7.66	6.18-9.40	9.37
	#3	180	7.59	5.94-9.40	9.43
	#4	246	7.62	5.94-9.40	9.43
Galvanized	#1	70	7.68	6.50-8.60	9.49
	#2	131	7.66	6.18-9.40	9.37
	#3	180	7.59	5.94-9.40	9.43
	#4	246	7.62	5.94-9.40	9.43
Loop #4					
Copper	#1	70	7.76	7.10-8.70	9.12
	#2	103	7.71	7.10-8.72	9.26
	#3	131	7.82	6.15-8.72	9.20
	#4	180	7.79	6.15-8.72	9.29
Iron	#1	70	7.76	7.10-8.70	9.12
	#2	131	7.71	7.10-8.72	9.26
	#3	180	7.82	6.15-8.72	9.20
	#4	246	7.79	6.15-8.72	9.29
Galvanized	#1	70	7.76	7.10-8.70	9.12
	#2	131	7.71	7.10-8.72	9.26
	#3	180	7.82	6.15-8.72	9.20
	#4	246	7.79	6.15-8.72	9.29

*Based on daily $[H^+]$ x hrs. exposure, averaged over each coupon's exposure period.

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TABLE B-2. TEST LOOP QUALITY CONTROL (SUMMARIZED IN 2-WEEK PERIODS)

	Loop #1				Loop #2			
Time Interval	Average pH	pH Range	$[H^+] \times 10^{-7}$	Total Alkalinity	Average pH	pH Range	$[H^+] \times 10^{-7}$	Total Alkalinity
1979 11/9-11/19	6.04	5.95-6.13	1.24	-	7.38	6.58-8.80	5.32	-
11/19-11/29	6.13	6.08-6.29	1.05	-	7.49	6.92-8.00	1.72	-
1980 5/1-5/14	6.02	5.90-6.08	0.99	0.8	7.66	7.35-7.97	1.01	10.4
5/14-5/27	5.89	5.83-6.05	2.08	-	7.60	7.19-8.50	1.29	-
5/27-6/11	6.00	5.80-6.12	2.27	0.4	7.74	7.71-8.11	0.69	11.8
6/11-6/25	5.89	5.40-6.30	9.33	0.8	7.38	6.10-8.10	10.4	6.4
6/25-7/9	6.07	5.92-6.18	0.90	0.9	7.60	7.35-8.70	1.29	10.6
7/9-7/23	5.80	5.20-6.15	13.8	2.2	7.50	6.6-8.05	3.62	12.7
7/23-8/6	5.94	5.80-6.18	2.46	-	7.45	6.50-8.20	4.65	-
8/6-8/20	5.95	5.82-6.15	2.04	.95	7.01	6.22-8.30	16.7	9.1
8/20-9/3	6.07	5.99-6.22	1.38	-	7.77	7.15-8.02	0.78	-
9/3-9/17	6.05	5.92-6.12	1.24	1.4	7.69	7.30-8.11	0.75	6.4
9/17-10/1	6.12	6.02-6.20	0.85	1.5	7.61	6.38-8.55	5.33	9.0
10/1-10/15	6.21	6.08-6.30	0.82	1.6	7.90	7.44-8.15	0.40	9.0
10/15-10/29	6.20	6.09-6.30	0.92	1.3	7.48	6.50-8.30	3.81	7.6
10/29-11/12	6.09	5.94-6.21	1.82	-	7.73	7.40-8.02	0.36	-
11/12-11/26	6.10	6.00-6.30	1.72	1.1	7.64	6.90-8.50	1.75	8.3
11/26-12/12 Shutdown	6.08	6.00-6.15	1.09	1.7	7.50	6.25-8.40	3.14	11.5

TABLE B-2. TEST LOOP QUALITY CONTROL (SUMMARIZED IN 2-WEEK PERIODS), CONT.

Time Interval	Loop #3 Average pH	Loop #3 pH Range	Loop #3 $[H^+] \times 10^{-7}$	Loop #3 Total Alkalinity	Loop #4 Average pH	Loop #4 pH Range	Loop #4 $[H^+] \times 10^{-7}$	Loop #4 Total Alkalinity
1979								
11/9-11/19	7.57	7.20-8.15	1.41	-	7.67	7.4-7.97	0.90	-
11/19-11/29	7.69	7.61-8.20	0.64	-	7.75	7.32-8.02	0.65	-
1980								
5/1-5/14	7.58	7.20-8.07	2.98	24.4	7.76	7.10-8.07	0.98	23.8
5/14-5/27	7.76	7.09-8.60	1.09	-	7.69	7.21-8.26	.21	-
5/27-6/11	7.66	6.5-8.45	3.91	18.6	7.91	7.30-8.70	0.60	20.6
6/11-6/25	8.01	7.65-9.4	0.33	13.4	7.89	7.71-8.25	0.87	15.6
6/25-7/9	7.92	7.40-8.35	0.45	16.2	7.95	7.31-8.72	0.68	18.8
7/9-7/23	7.49	6.18-8.38	.86	20.4	7.34	6.15-8.41	9.44	20.6
7/23-8/6	7.74	7.99-8.40	1.53	-	7.58	6.6-8.35	2.79	-
8/6-8/20	7.21	5.94-8.41	1.45	18.5	7.74	6.75-8.32	1.55	17.0
8/20-9/3	7.53	6.70-8.40	3.01	-	7.87	7.01-8.24	1.16	-
9/3-9/17	7.62	7.15-8.48	2.72	9.4	7.82	7.10-8.15	0.90	9.6
7/17-10/1	7.42	6.40-8.24	5.09	16.8	7.55	6.75-8.21	2.45	16.4
10/1-10/15	7.93	7.60-8.48	0.72	15.7	7.90	7.16-8.42	1.05	16.2
10/15-10/29	7.83	7.20-8.51	0.76	19.2	7.89	7.10-8.65	0.54	15.3
10/29-11/12	7.84	7.45-8.13	0.37	-	7.83	7.45-8.23	0.48	-
11/12-11/26	7.69	7.30-9.5	1.36	18.8	7.85	7.25-8.5	0.86	-
11/26-12/12	7.93	7.5-8.18	0.35	17.8	7.88	7.20-8.20	0.76	19.9
Shutdown								

TABLE B-3. CALCULATED CHEMICAL DOSAGES BASED ON PERIODIC CHEMICAL ANALYSIS.

Date	Constituent	Loop #1	Loop #2	Loop #3	Loop #4
5/18/80	pH	6.00	7.35	8.00	7.95
	Total Alkalinity (mg/L $CaCO_3$)	0.08	10.4	24.4	23.8
	Specific Conductance (µmhos)	26.7	44.5	71.6	68.6
	Ca (mg/L $CaCO_3$)	6.6	8.8	11.9	9.6
	Na (mg/L)	0.95	4.4	8.9	9.75
	Na_2CO_3 Dosage (mg/L)	-	7.95	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	29.0	23.0
	CaO Dosage (mg/L)	-	1.21	2.95	1.67
	SiO_2	5.45	-	-	10.9
	SiO_2 Dosage (mg/L)	-	-	-	5.45
5/15/80	SiO_2	5.3	-	-	10.1
	SiO_2 Dosage (mg/L)	-	-	-	4.8
5/23/80	SiO_2	5.4	-	-	10.0
	SiO_2 Dosage (mg/L)	-	-	-	4.6
6/10/80	pH	-	7.89	8.01	8.00
	Total Alkalinity (mg/L $CaCO_3$)	0.4	11.8	18.6	20.6
	Specific Conductance (µmhos)	26.5	47.0	61.6	67.2
	Ca (mg/L $CaCO_3$)	7.1	9.4	13.8	11.1
	Na (mg/L)	1.32	5.00	6.45	8.40
	Na_2CO_3 Dosage (mg/L)	-	8.5	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	18.75	23.0
	CaO Dosage (mg/L)	-	1.29	3.79	2.27
	SiO_2	-	5.5	5.5	8.85
	SiO_2 Dosage (mg/L)	-	-	-	3.35
6/17/80	pH	6.01	7.81	8.12	8.01
	Total Alkalinity (mg/L $CaCO_3$)	1.0	11.8	15.6	16.8
	Specific Conductance (µmhos)	27.0	47.0	55.9	57.8
6/23/80	SiO_2	5.35	-	-	10.9
	SiO_2 Dosage (mg/L)	-	-	-	5.55
6/24/80	pH	6.08	7.89	8.01	8.02
	Total Alkalinity (mg/L $CaCO_3$)	0.8	6.4	13.4	15.6
	Specific Conductance (µmhos)	26.2	36.3	48.6	54.0
	Ca (mg/L $CaCO_3$)	7.4	7.0	9.8	8.0
	Na (mg/L)	0.92	3.65	5.35	7.6
	Na_2CO_3 Dosage (mg/L)	-	6.3	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	16.2	21.7
	CaO Dosage (mg/L)	-	off	1.59	0.57
	SiO_2	-	5.1	-	8.3
	SiO_2 Dosage (mg/L)	-	-	-	3.2

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TABLE B-3, CONT.

Date	Constituent	Loop #1	Loop #2	Loop #3	Loop #4
7/8/80	pH	-	7.91	7.98	8.04
	Total Alkalinity (mg/L $CaCO_3$)	0.9	10.6	16.2	18.8
	Specific Conductance (µmhos)	26.6	43.7	55.6	59.9
	SiO_2	5.3			8.8
	SiO_2 Dosage (mg/L)				3.5
7/14/80	Total Alkalinity (mg/L $CaCO_3$)	2.2	12.7	20.4	20.6
	Specific Conductance (µmhos)	26.2	46.4	59.6	61.5
	Ca (mg/L $CaCO_3$)	7.2	9.6	13.4	9.8
	Na (mg/L)	0.91	4.98	6.05	8.32
	Na_2CO_3 Dosage (mg/L)	-	9.4	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	18.8	21.8
	CaO Dosage (mg/L)	-	1.37	3.50	1.44
	SiO_2	5.6	-	-	11.8
	SiO_2 Dosage (mg/L)	-	-	-	6.2
7/25/80	SiO_2	5.25	-	-	10.05
	SiO_2 Dosage (mg/L)	-	-	-	4.8
8/11/80	SiO_2	5.2	-	-	10.7
	SiO_2 Dosage (mg/L)	-	-	-	5.5
8/19/80	pH	5.95	7.80	7.92	7.90
	Total Alkalinity (mg/L $CaCO_3$)	.95	9.1	18.5	17.0
	Specific Conductance (µmhos)	2.69	40.8	58.7	55.5
	Ca (mg/L $CaCO_3$)	7.7	9.1	12.0	8.6
	Na (mg/l)	0.93	4.04	6.89	7.46
	Na_2CO_3 Dosage (mg/L)	-	7.15	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	21.75	19.5
	CaO Dosage (mg/L)	-	0.80	2.43	0.53
	SiO_2	5.45			10.65
	SiO_2 Dosage (mg/L)				5.20
9/4/80	pH	6.08	7.83	7.93	7.93
	Total Alkalinity (mg/L $CaCO_3$)	1.4	6.4	9.4	9.6
	Specific Conductance (µmhos)	29.4	38.1	44.4	45.0
	Ca (mg/L $CaCO_3$)	8.2	8.5	12.1	9.8
	Na (mg/L)	0.92	2.52	2.45	4.00
	Na_2CO_3 Dosage (mg/L)	-	3.7	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	7.5	5.6
	CaO Dosage (mg/L)	-	0.46	2.20	0.91
	SiO_2	5.5	-	-	10.0
	SiO_2 Dosage (mg/L)				4.5
9/19/80	SiO_2	4.4			8.8
	SiO_2 Dosage (mg/L)				4.4

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TABLE B-3, CONT.

Date	Constituent	Loop #1	Loop #2	Loop #3	Loop #4
9/25/80	pH	5.95	7.80	7.92	7.90
	Total Alkalinity (mg/L $CaCO_3$)	.95	9.1	18.5	17.0
	Specific Conductance (μmhos)	29.7	42.9	58.1	58.6
	Ca (mg/L $CaCO_3$)	7.4	9.0	11.6	9.3
	Na (mg/L)	0.91	3.50	5.65	6.80
	Na_2CO_3 Dosage (mg/L)	-	6.0		
	$NaHCO_3$ Dosage (mg/L)	-	-	17.3	17.8
	CaO Dosage (mg/L)	-	0.91	2.36	1.06
	SiO_2	5.1	-	-	9.5
	SiO_2 Dosage (mg/L)	-	-	-	4.4
10/8/80	pH	6.0	7.85	7.89	7.93
	Total Alkalinity (mg/L $CaCO_3$)	1.6	9.0	15.7	16.2
	Specific Conductance (μmhos)	26.4	39.1	50.3	50.8
	Ca (mg/L $CaCO_3$)	8.0	9.1	11.9	9.5
	Na (mg/L)	0.94	3.90	5.42	6.80
	Na_2CO_3 Dosage (mg/L)	-	6.8	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	16.4	18.0
	CaO Dosage (mg/L)	-	0.61	2.20	0.84
	SiO_2	5.3	-	-	9.4
	SiO_2 Dosage (mg/L)	-	-	-	4.1
10/22/80	pH	6.20	7.91	8.00	7.98
	Total Alkalinity (mg/L $CaCO_3$)	1.3	7.6	19.2	15.3
	Specific Conductance (μmhos)	26.9	37.2	57.2	50.7
	Ca (mg/L $CaCO_3$)	7.7	9.0	11.8	9.6
	Na (mg/L)	0.98	3.36	7.26	6.65
	Na_2CO_3 Dosage (mg/L)	-	5.5	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	22.9	18.5
	CaO Dosage (mg/L)	-	0.72	2.28	1.22
	SiO_2	7.05	-	-	12.33
	SiO_2 Dosage (mg/L)	-	-	-	5.28
11/5/80	SiO_2	8.04			13.8
	SiO_2 Dosage (mg/L)				5.04
	Specific Conductance (μmhos)	27.0			49.5
11/19/80	pH	6.13	7.95	7.99	7.99
	Total Alkalinity (mg/L $CaCO_3$)	1.1	8.3	18.8	L/A
	Specific Conductance (μmhos)	25.6	38.4	53.7	47.9
	Ca (mg/L $CaCO_3$)	7.4	8.6	11.4	-
	Na (mg/L)	0.90	3.60	6.87	6.00
	Na_2CO_3 Dosage (mg/L)	-	6.2	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	2.18	15.2
	CaO (mg/L $CaCO_3$)	-	0.68	2.25	L/A
	SiO_2	5.5	-	-	9.6
	SiO_2 Dosage (mg/L)	-	-	-	4.1

(continued)

TABLE B-3, CONT.

Date	Constituent	Loop #1	Loop #2	Loop #3	Loop #4
12/2/80	pH	6.15	7.83	7.98	7.97
	Total Alkalinity (mg/L $CaCO_3$)	1.5	12.0	L/A	22.0
	Specific Conductance (μmhos)	26.0	43.2	-	60.7
	Ca (mg/L $CaCO_3$)	7.2	9.6	L/A	11.5
	Na (mg/L)	0.91	5.05	L/A	8.2
	Na_2CO_3 Dosage (mg/L)	-	9.54	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	-	24.15
	CaO Dosage (mg/L)	-	1.37	-	2.43
	SiO_2	6.0	-	-	8.95
	SiO_2 Dosage (mg/L)	-	-	-	2.95
12/12/80	pH	6.15	7.81	7.87	7.89
	Total Alkalinity (mg/L $CaCO_3$)	1.18	11.0	17.8	17.7
	Specific Conductance (μmhos)	26.3	42.5	53.8	52.5
	Ca (mg/L $CaCO_3$)	7.8	9.4	13.6	12.4
	Na (mg/L)	0.90	4.70	5.62	5.99
	Na_2CO_3 Dosage (mg/L)	-	8.8	-	-
	$NaHCO_3$ Dosage (mg/L)	-	-	17.2	16.1
	CaO Dosage (mg/L)	-	0.91	3.27	2.58
	SiO_2	5.9	-	-	8.85
	SiO_2 Dosage (mg/L)	-	-	-	2.95

L/A = Lab accident.

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TABLE B-4. METAL LEACHING TEST SECTIONS - FLOW AND VELOCITY SUMMARIZATION

Time Interval 1980	Flow ($L/sec \times 10^{-3}$)				Velocity in Copper Pipe (cm/sec)							
					50/50 Lead/Tin Solder				95/5 Tin/Antimony Solder			
	Loop #1	Loop #2	Loop #3	Loop #4	Loop #1	Loop #2	Loop #3	Loop #4	Loop #1	Loop #2	Loop #3	Loop #4
5/22- 6/24	6.59	6.70	6.42	6.53	16.0	16.2	15.5	15.8	15.8	16.0	15.4	15.6
6/26- 7/14	6.63	7.63	6.51	6.58	16.1	16.1	15.8	15.9	15.9	15.9	15.6	15.7
7/16- 8/19	6.57	6.47	6.58	6.58	15.9	15.7	15.9	15.9	15.7	15.5	15.7	15.7
8/21- 9/04	6.53	6.57	6.64	6.44	15.8	15.9	16.1	15.6	15.6	15.7	15.9	15.4
9/06- 9/25	6.67	6.49	6.41	6.59	16.2	15.7	15.5	16.0	16.0	15.5	15.3	15.8
9/27-10/22	6.57	6.48	6.65	6.60	15.9	15.7	16.1	16.0	15.7	15.5	15.9	15.8
10/24-11/19	10.0	9.95	9.97	9.95	24.2	24.1	24.1	23.9	23.9	23.8	23.9	23.6
11/23-12/02	10.2	9.70	10.1	9.86	24.7	23.5	24.5	23.9	24.4	23.2	24.2	23.6
12/04-12/12	9.84	9.00	10.1	9.69	23.8	21.8	24.5	23.5	23.5	21.5	24.2	23.2

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TABLE B-4. METAL LEACHING TEST SECTIONS - FLOW AND VELOCITY SUMMARIZATION, CONT.

Time Interval 1980	Flow ($L/sec \times 10^{-3}$)				Velocity in Copper Pipe (cm/sec)				Velocity in Galvanized Pipe (cm/sec)			
	Loop #1	Loop #2	Loop #3	Loop #4	Loop #1	Loop #2	Loop #3	Loop #4	Loop #1	Loop #2	Loop #3	Loop #4
5/22- 6/24	6.59	6.70	6.42	6.53	13.4	13.6	13.0	13.3	10.6	10.8	10.3	10.5
6/26- 7/14	6.63	7.63	6.51	6.58	13.5	13.5	13.2	13.4	10.7	10.7	10.5	10.6
7/16- 8/19	6.57	6.47	6.58	6.58	13.3	13.1	13.4	13.4	10.6	10.4	10.6	10.6
8/21- 9/04	6.53	6.57	6.64	6.44	13.3	13.3	13.5	13.1	10.5	10.6	10.7	10.4
9/06- 9/25	6.67	6.49	6.41	6.59	13.5	13.2	13.0	13.4	10.7	10.5	10.3	10.6
9/27-10/22	6.57	6.48	6.65	6.60	13.3	13.2	13.5	13.4	10.6	10.4	10.7	10.6
10/24-11/19	10.0	9.95	9.97	9.95	20.3	20.2	20.2	20.0	16.1	16.0	16.1	15.9
11/23-12/02	10.2	9.70	10.1	9.86	20.7	19.7	20.5	20.0	16.4	15.6	16.3	15.9
12/04-12/12	9.84	9.00	10.1	9.69	20.0	18.3	20.5	19.7	15.9	14.5	16.3	15.6

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APPENDIX C. IRON PITTING ANALYSIS RESULTS

Days Exposure	Test Loop #	Iron Corrosion Type	% Surface Attacked	Average Pit Depth* mils	Maximum Pit Depth mils	Penetration Rate mils/yr
70	1	General uneven & semi-local uneven	30	15.4	18.0	80.3
	2	Semi-local uneven	20	17.7	20.5	92.3
	3	Semi-local uneven	25	20.0	23.5	104
	4	Wide pits	5	23.7	27.7	123
131	1	Semi-local uneven & wide pits	60	17.9	22.6	49.9
	2	Semi-local uneven	50	19.5	20.8	54.3
	3	Semi-local uneven & wide pits	10	17.8	21.0	49.6
	4	Semi-local uneven	20	26.3	28.9	73.3
180	1	Semi-local uneven & wide pits	5	19.8	25.3	40.2
	2	Semi-local uneven	10	25.5	33.9	51.7
	3	Semi-local uneven	5	25.1	28.4	50.9
	4	Semi-local uneven	40	23.9	26.5	48.5
236	1	Semi-local uneven & wide pits	60	28.2	34.0	43.6
	2	Semi-local uneven	60	26.8	29.8	41.4
	3	Semi-local uneven	60	19.8	23.8	30.6
	4	Semi-local uneven	40	25.5	27.5	39.4

*Based on the average of 10 deepest pits - each coupon.

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APPENDIX D

METAL LOSSES THROUGH MEMBRANE FILTRATION

DETERMINATION OF LEACH LOOP TEST WATER pH AFTER 24 HOURS CONTACT

Procedure

a. Cu, Cu + Pb/Sn solder, and galvanized 1/4" leach tubing were reconditioned by running Water Quality Laboratory water through them for four days.

b. Control tubing sections were filled with Tolt water at 9:30 a.m. May 27, 1981; pH = 6.33.

c. Treatment tubing sections were filled at 11:00 a.m. time with Tolt water adjusted to pH 8.08 with soda ash.

d. 24 hours later, each test water was retested for pH, filtered through .45 µ Millipore membrane and retested for pH.

Results

The results of the pH tests are listed in Table D-1.

TABLE D-1. METAL LEACHING pH TEST RESULT

Specimen	Original pH	pH After 24 Hours Contact	Post-Filtration pH
Cu	6.33	6.37	6.59
Cu + Pb/Sn	6.33	6.56	6.74
Zn	6.33	7.12	L/A
Cu	8.08	8.09	8.09
Cu + Pb/Sn	8.08	8.09	8.13
Zn	8.08	8.53	8.39

L/A = Lab accident.

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Since target pH's for pilot studies were approximately 7.9, we must compare filtration losses at pH 6.6 and 7.9 to determine if the relative metal losses between treatments are valid.

DETERMINATION OF METAL LOSSES IN MEMBRANE FILTRATION

Procedure

a. Stock solutions of approximately 1000 mg/L Cu, Pb, and Zn were made from the acetate salts of each metal without acidification to prevent abnormally high ion levels in the test waters.

b. Two portions of Tolt distribution water were spiked with the stock solutions to obtain the following concentrations:

Low Concentration:	20	µg/L Pb
	0.4	mg/L Cu
High Concentration:	200	µg/L Pb
	1.5	mg/L Cu
	20.0	mg/L Zn

c. The low concentration portion was adjusted with $Ca(OH)_2$ to pH 8.7 and prefiltered through .45 µm membrane filter to eliminate suspended metal particulates. Following the prefiltration, the pH equaled 7.85.

d. One-half of the prefiltered low concentration portion was adjusted to pH 6.6 with dilute HNO_3.

e. Three replicates of each low concentration pH 6.6 and low concentration pH 7.85 were filtered through the apparatus following the normal procedures used during the pilot plant studies. A control (unfiltered) portion was preserved from both test waters.

f. The high concentration portion was adjusted to pH 7.95 with $Ca(OH)_2$. Considerably more lime was needed to compensate for the high zinc acetate concentration. It was then prefiltered through 25 um and 8 um paper filters and finally through a 0.45 µm membrane. The pH after prefiltration was 7.85.

g. One-half of the high concentration portion was then adjusted to pH 7.60 with dilute HNO_3.

h. Three replicates were filtered as before and control portions preserved.

i. The final filtration step used here and during the pilot plant tests consisted of: Acid (1:1 HCl and 1:1 HNO_3) washing the all-glass (Pyrex Millipore funnel) apparatus and distilled water risning before beginning); distilled water rinsing (3 times) between each sample; use of a new 0.45 um Millipore filter for each portion (rinsed with distilled water); the filtered and control 10 ml portions were placed in pre-acidified (½% HNO_3) Pyrex bottles.

Results

The resulted are listed in Table D-2.

6-1/2"

TABLE D-2. METAL LOSS VIA FILTRATION

Pre-filtration pH	Dosages	Lead (µg/L)	Copper (mg/L)	Zinc (mg/L)
6.6	Pb ≃ 20 µg/L	17½	.18	
	Cu ≃ .4 mg/L	35½ (control)	.27	
		40½	.23	
		12½	.16	
6.7	Pb ≃ 200 µg/L	23	.09	4.72
	Cu ≃ 1.5 mg/L	38 (control)	.08	5.00
	Zn ≃ 20 mg/L	26	.095	4.92
		22½	.08	4.72
7.85	Pb ≃ 20 µg/L	16	.175	
7.85	Cu ≃ .4 mg/L	22½ (control)	.27	
		14	.155	
		16	.18	
7.85	Pb ≃ 200 µg/L	24	.07	5.24
7.85	Cu ≃ 1.5 mg/L	21 (control)	.075	5.00
	Zn ≃ 20 mg/L	29	.075	4.12
		29	.09	4.36

Conclusions:

1. No significant differences between pH 6.6-6.7 and pH 7.85 for metal losses via filtration.

2. Due to additional chances for contamination and metal losses, would not recommend filtering leachate in the future.

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APPENDIX E

SCANNING ELECTRON MICROSCOPY AND X-RAY DIFFRACTION TESTS

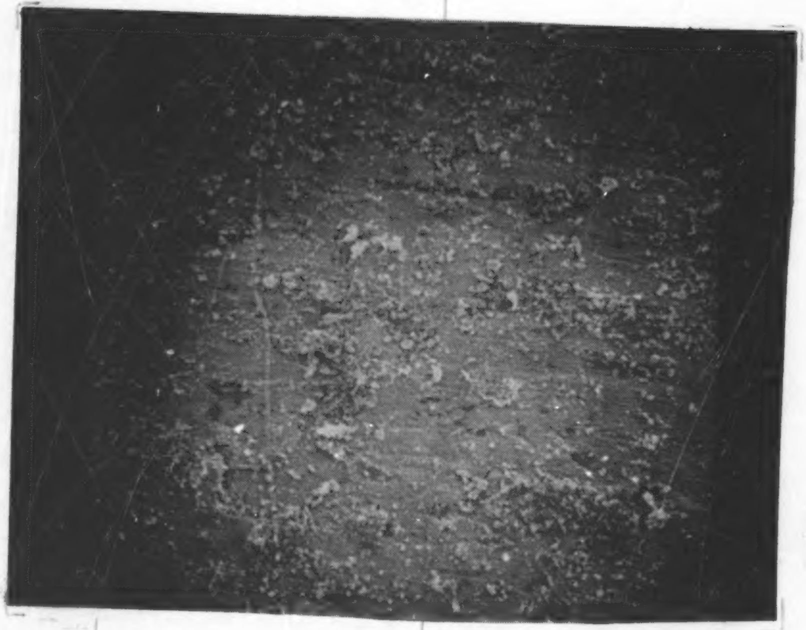

Figure E-1. SEM photograph of copper pipe corrosion film formed under control conditions and 0.12 m/s. (Magnification = 178X)

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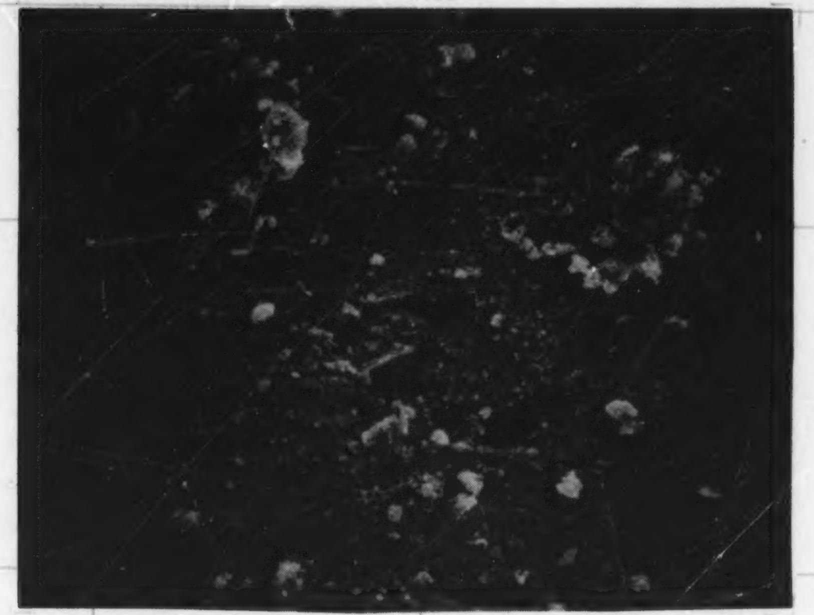

Figure E-2. SEM photograph of copper pipe corrosion film formed under control conditions and 0.12 m/s. (Magnification = 880X)

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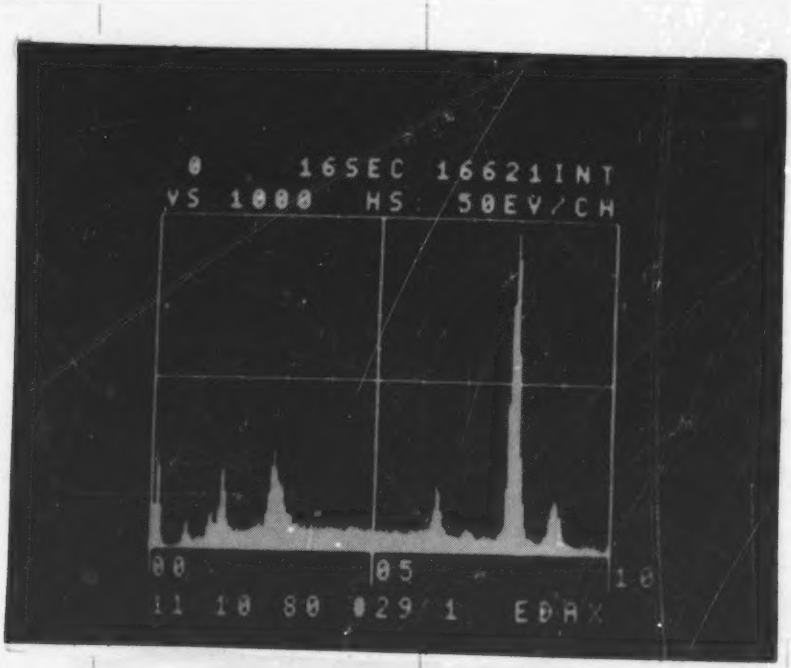

Figure E-3. EDAX analysis of copper pipe corrosion film formed under control conditions and 0.12 m/s.

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Figure E-4. SEM photograph of copper pipe corrosion film formed under control conditions and 0.18 m/s. (Magnification = 173X)

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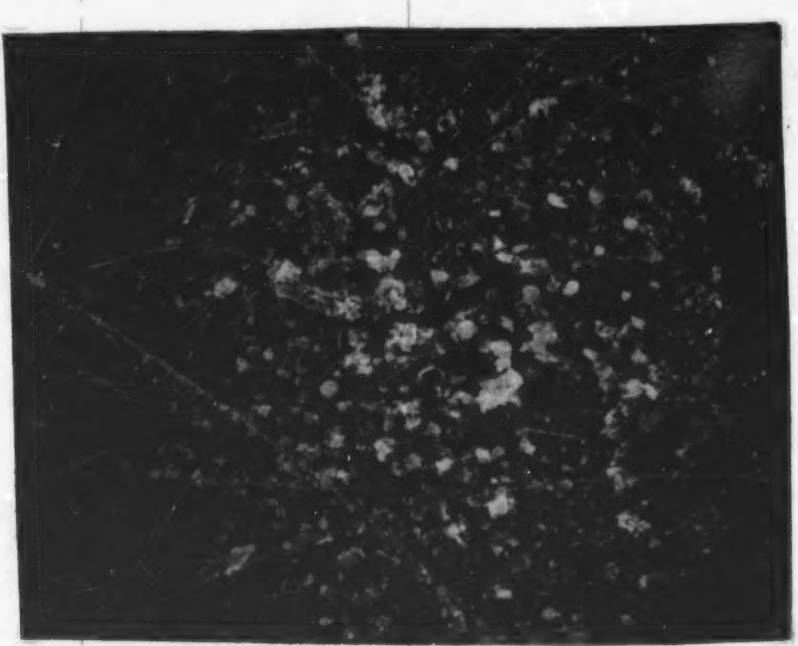

Figure E-5. SEM photograph of copper pipe corrosion film formed under control conditions and 0.18 m/s. (Magnification = 870X)

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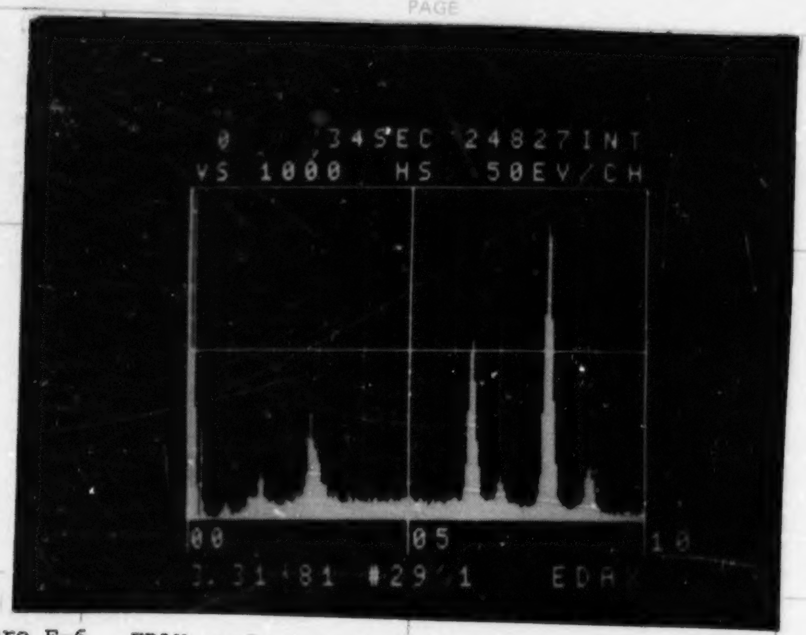

Figure E-6. EDAX analysis of copper pipe corrosion film formed under control conditions and 0.18 m/s.

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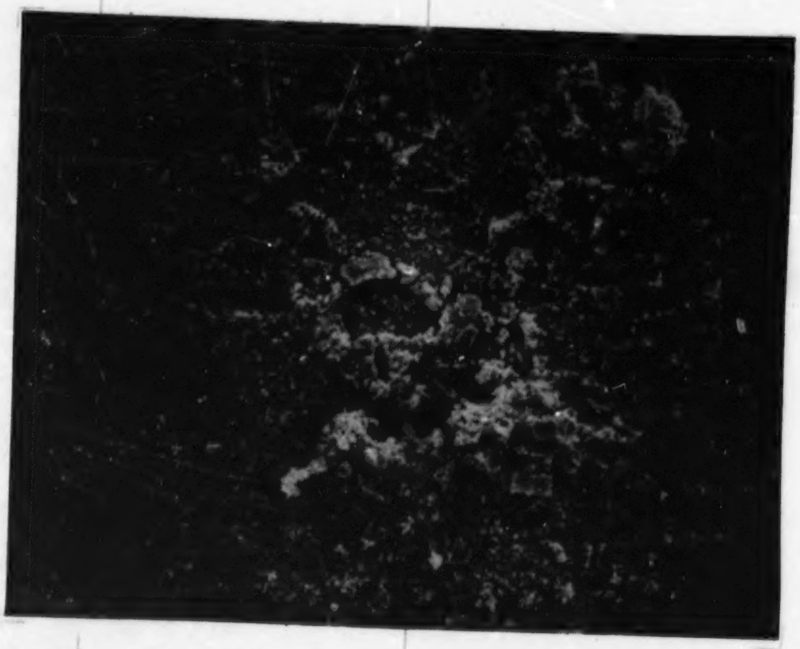

Figure E-7. SEM photograph of copper pipe corrosion film formed under lime/sodium carbonate treatment and 0.12 m/s. (Magnification = 175X)

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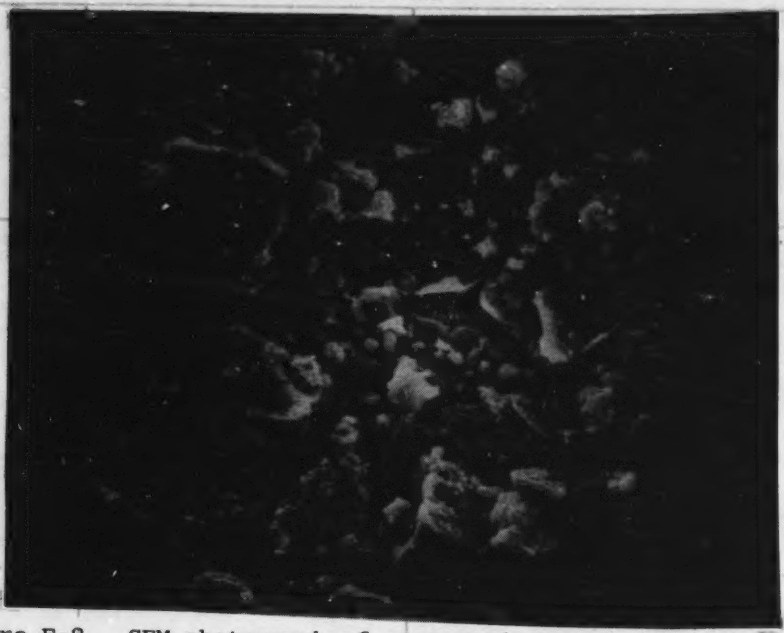

Figure E-8. SEM photograph of copper pipe corrosion film formed under lime/sodium carbonate treatment and 0.12 m/s. (Magnification = 875X)

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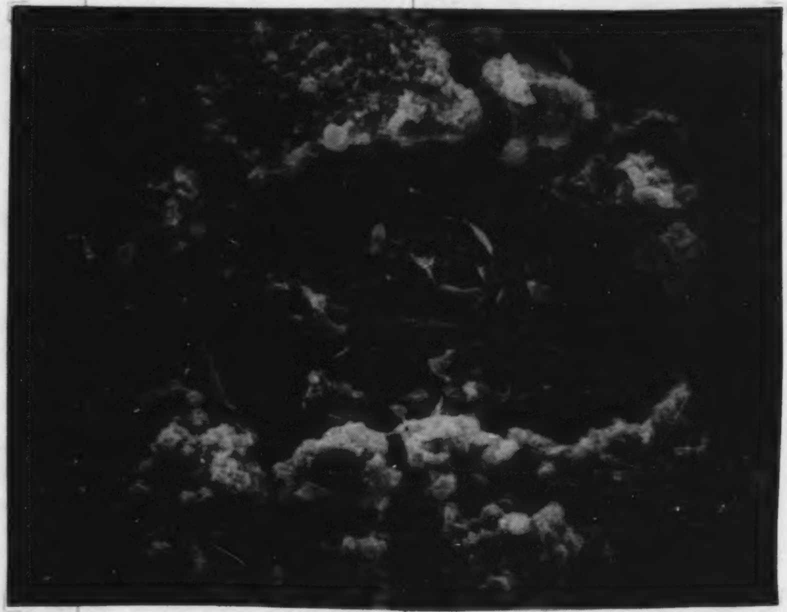

Figure E-9. SEM photograph of pits in copper pipe formed under lime/sodium carbonate treatment and 0.12 m/s. (Magnification = 875X)

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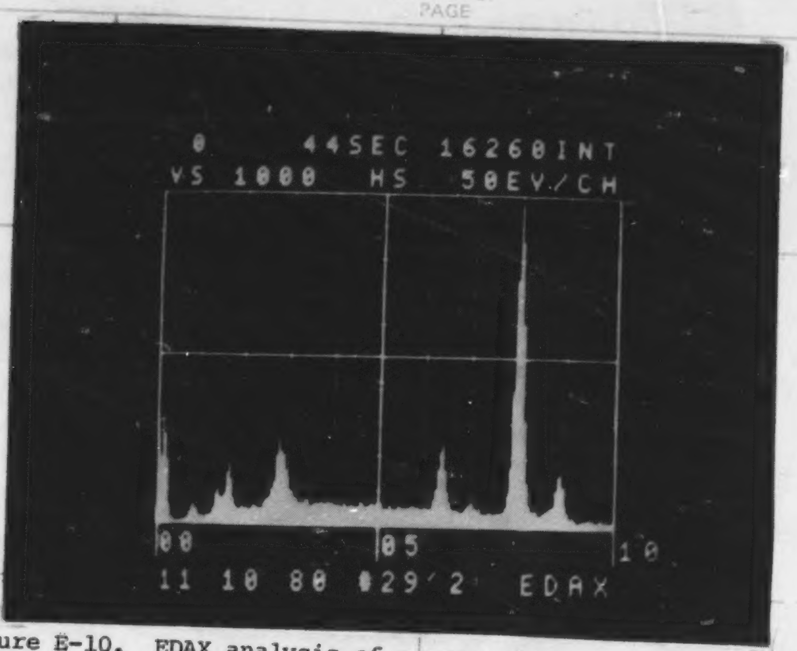

Figure E-10. EDAX analysis of copper pipe corrosion film formed under lime/sodium carbonate treatment and 0.12 m/s.

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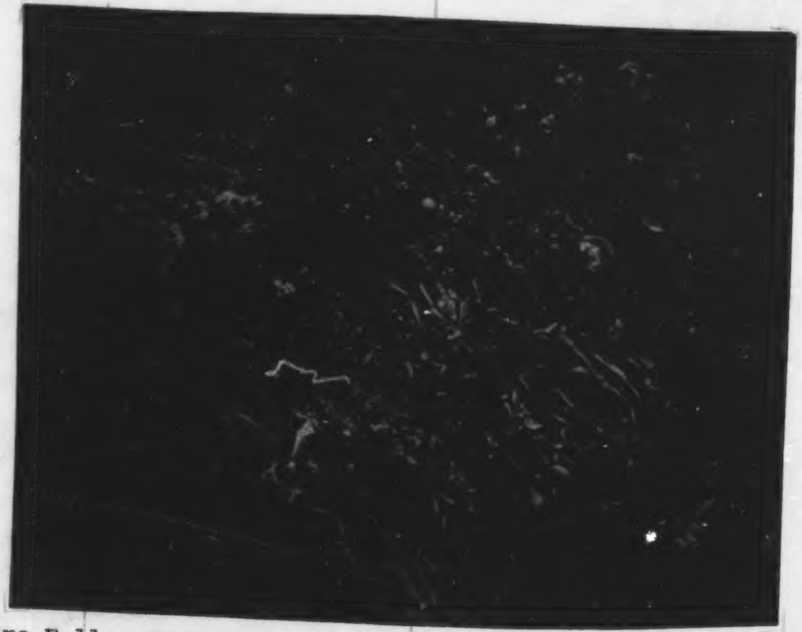

Figure E-11. SEM photograph of copper pipe corrosion film formed under lime/sodium carbonate treatment and 0.18 m/s. (Magnification = 176X)

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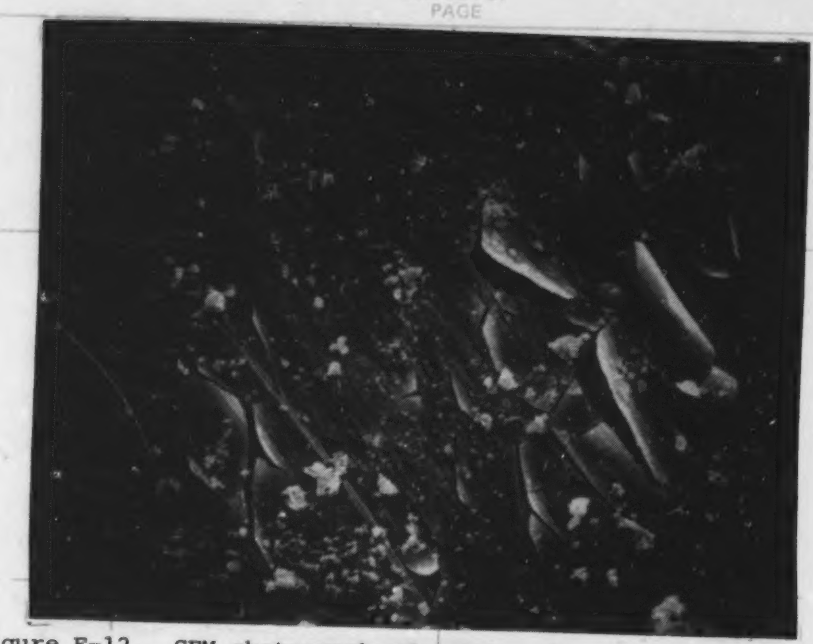

Figure E-12. SEM photograph of copper pipe corrosion film formed under lime/sodium carbonate treatment and 0.18 m/s. (Magnification = 880X)

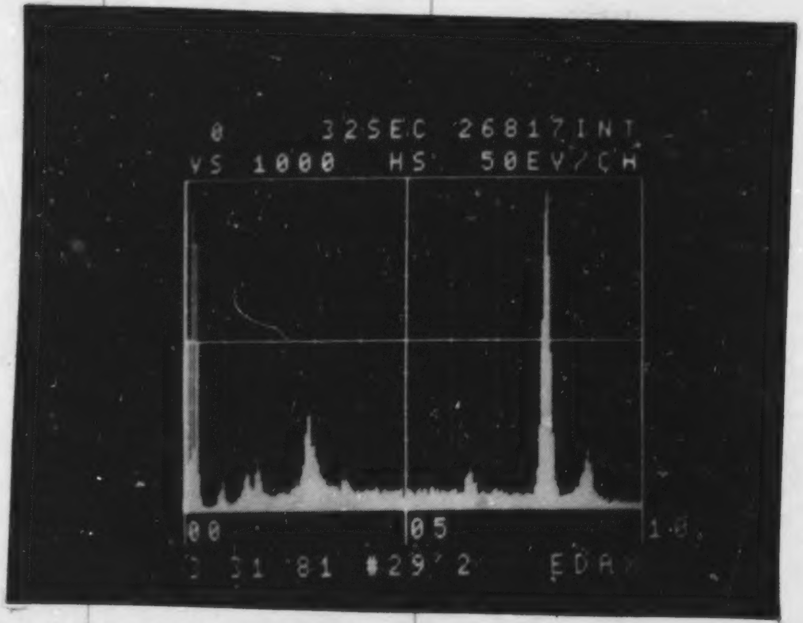

Figure E-13. EDAX analysis of copper pipe corrosion film formed under lime/sodium carbonate treatment and 0.18 m/s.

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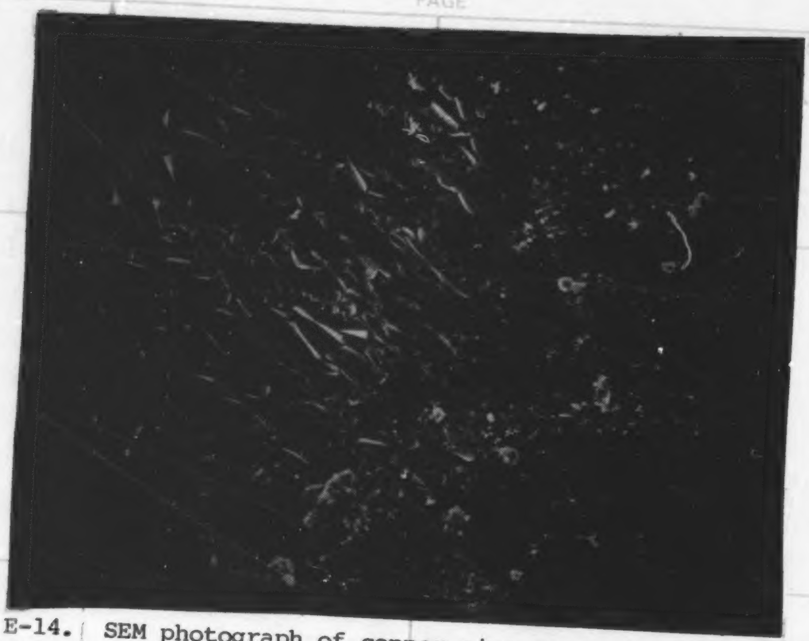

Figure E-14. SEM photograph of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.12 m/s. (Magnification = 170X)

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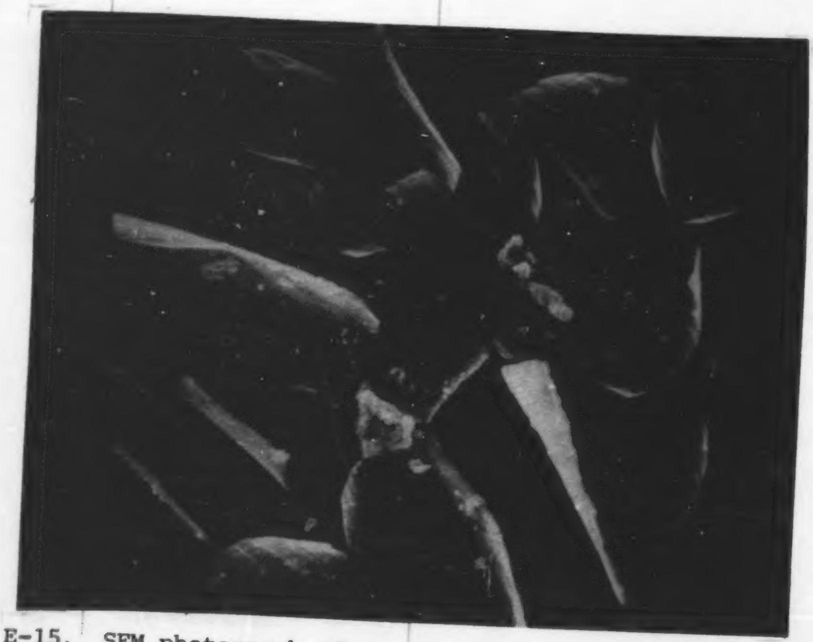

Figure E-15. SEM photograph of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.12 m/s. (Magnification = 850X)

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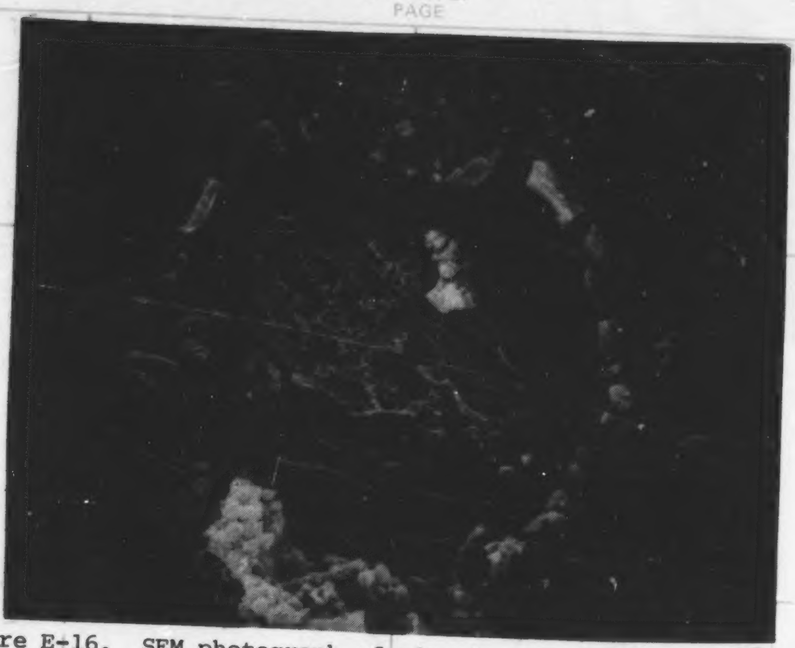

Figure E-16. SEM photograph of pits in copper pipe formed under lime/sodium bicarbonate treatment and 0.12 m/s. (Magnification = 850X)

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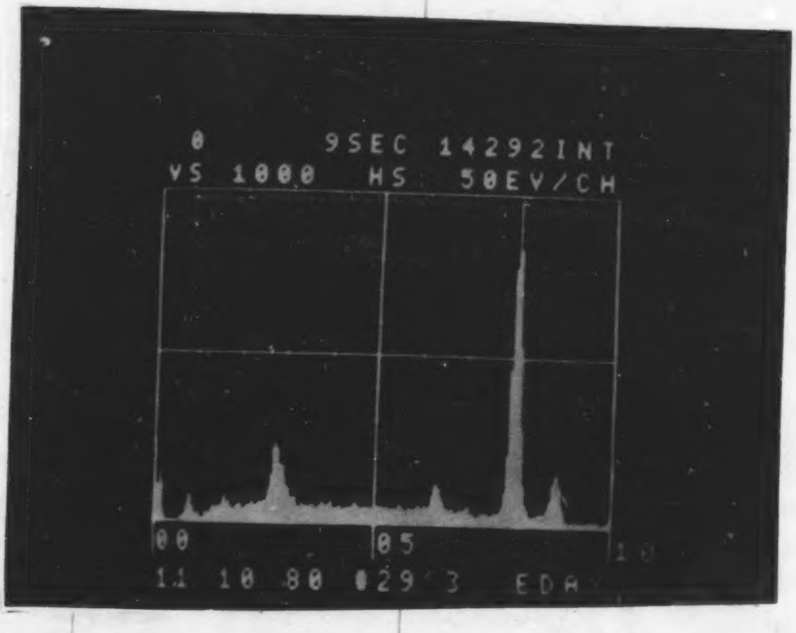

Figure E-17. EDAX analysis of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.12 m/s.

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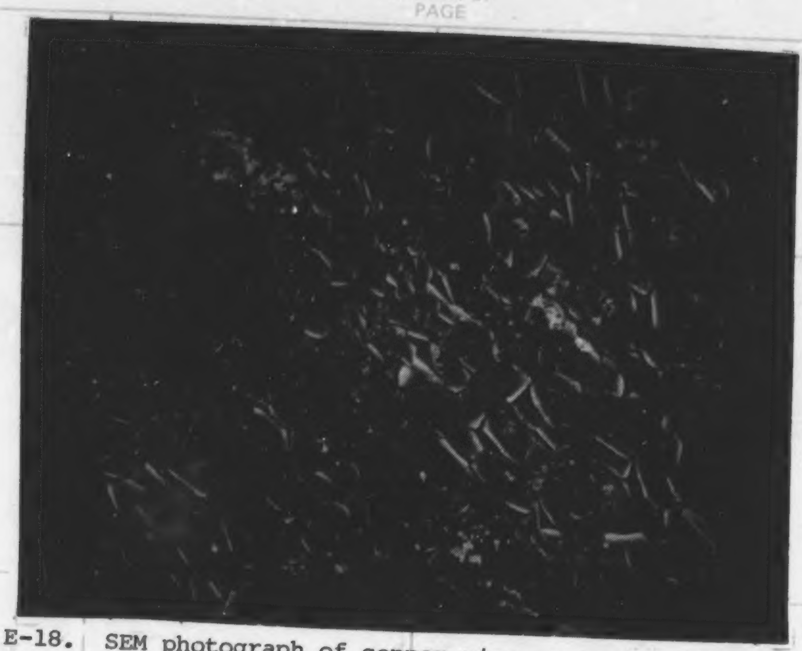

Figure E-18. SEM photograph of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s. (Magnification = 174X)

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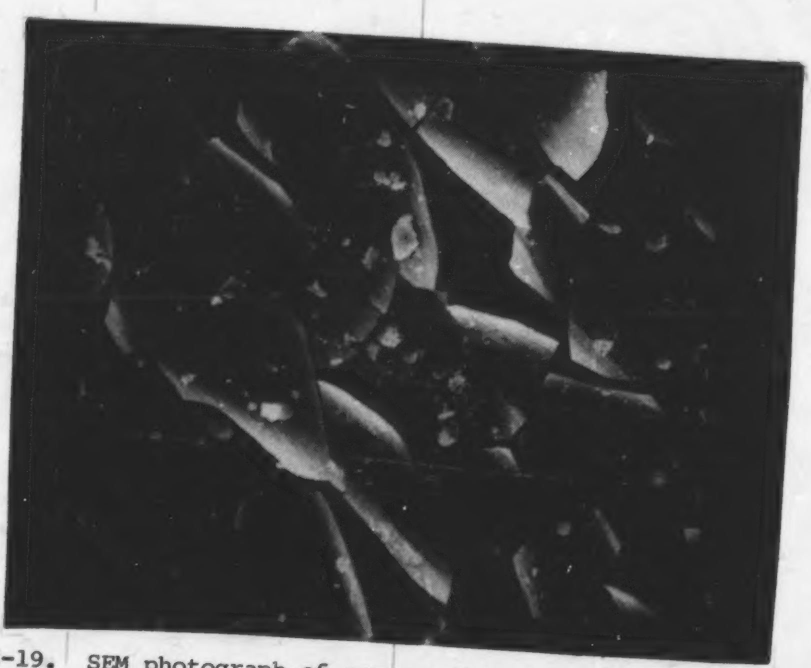

Figure E-19. SEM photograph of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s. (Magnification = 870X)

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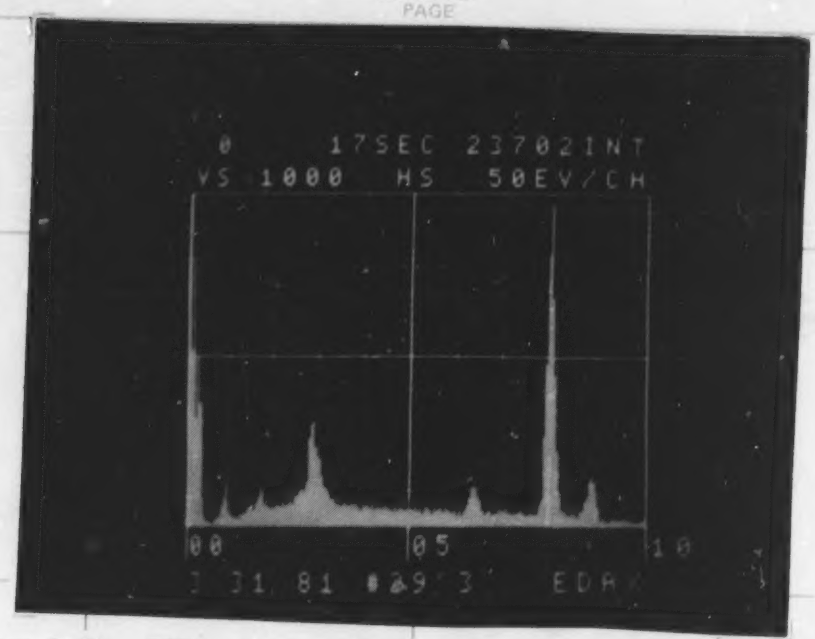

Figure E-20. EDAX analysis of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s.

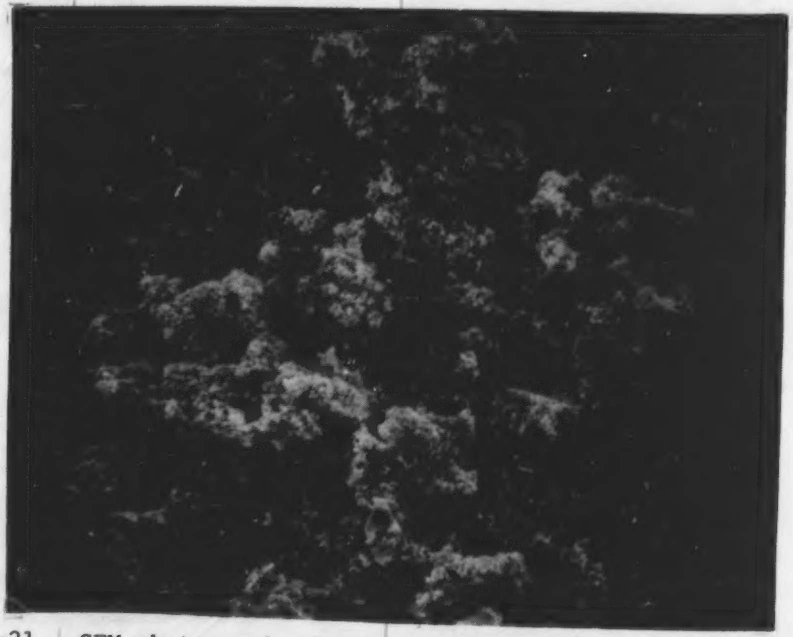

Figure E-21. SEM photograph of copper pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.12 m/s. (Magnification = 170X)

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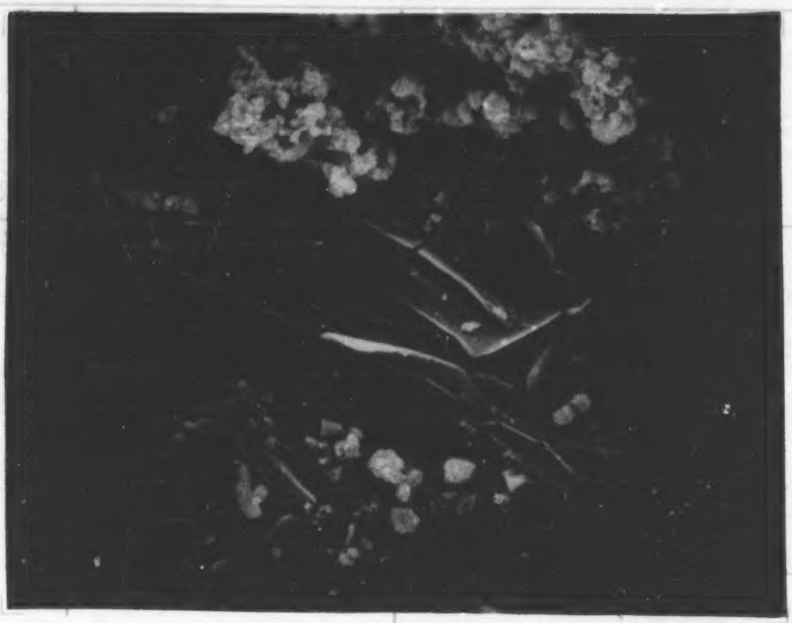

Figure E-22. SEM photograph of copper pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.12 m/s. (Magnification = 850X)

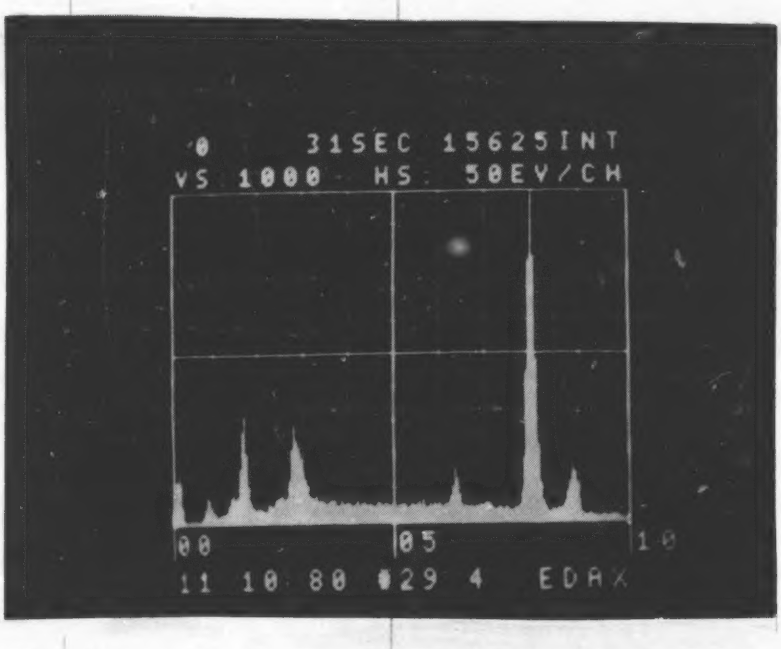

Figure E-23. EDAX analysis of copper pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.12 m/s.

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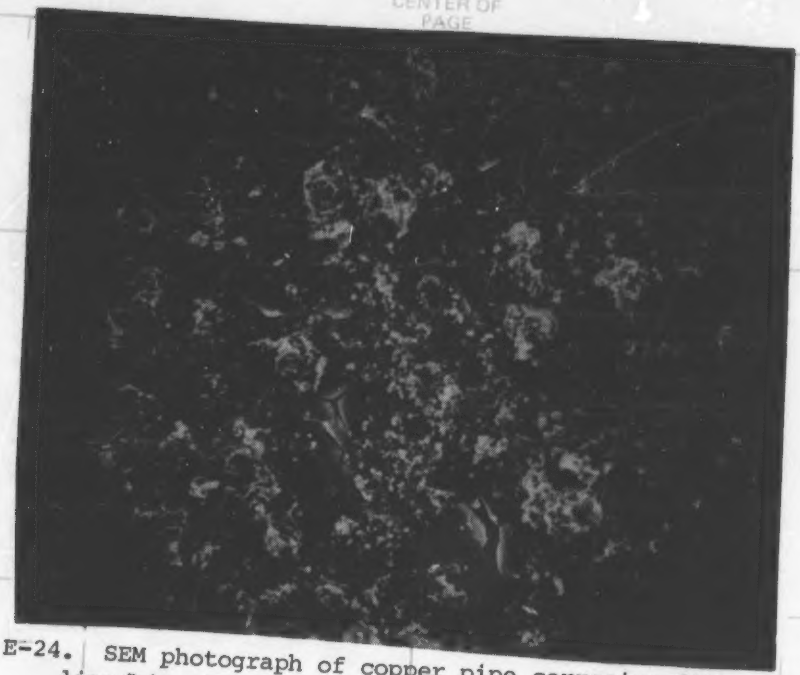

Figure E-24. SEM photograph of copper pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.18 m/s. (Magnification = 173X)

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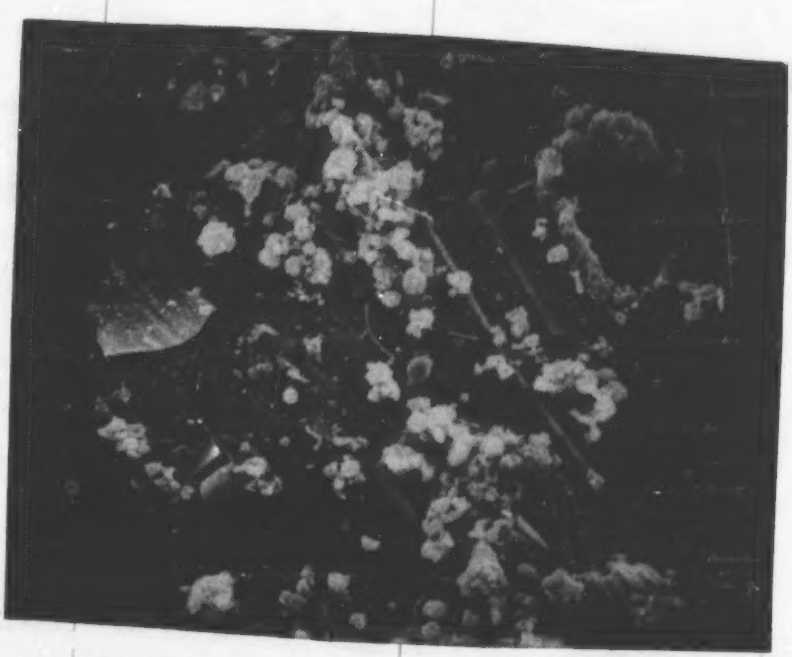

Figure E-25. SEM photograph of copper pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.18 m/s. (Magnification = 870X)

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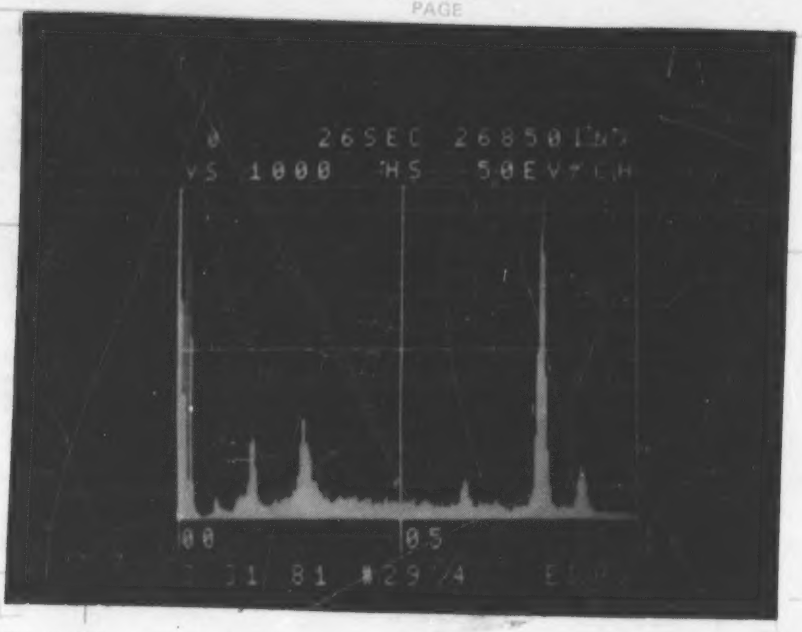

Figure E-26. EDAX analysis of copper pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s.

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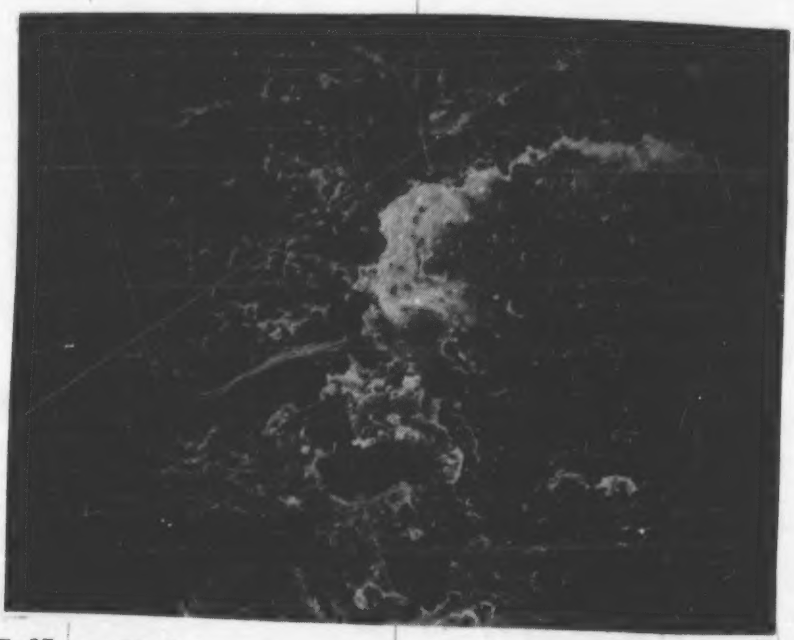

Figure E-27. SEM photograph of galvanized steel pipe corrosion film formed under control conditions and 0.12 m/s. (Magnification = 183X)

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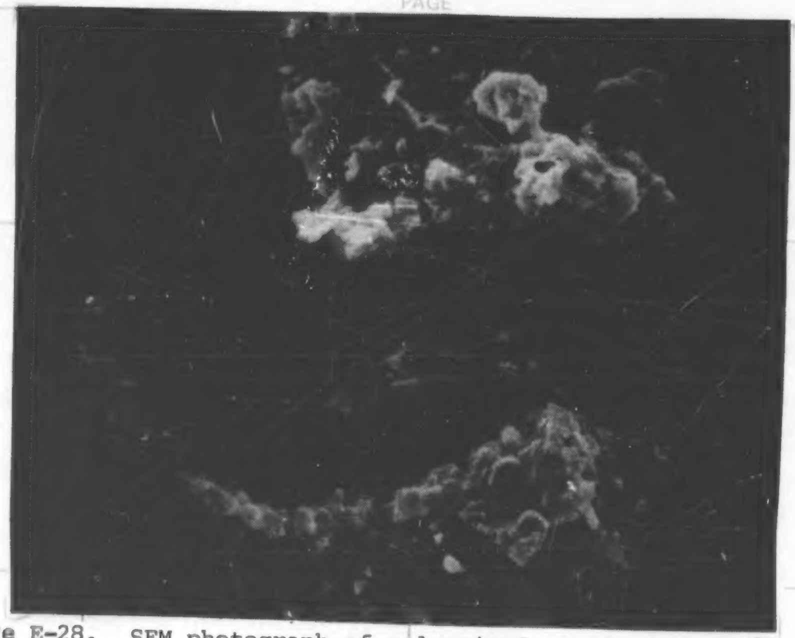

Figure E-28. SEM photograph of galvanized steel pipe corrosion film formed under control conditions and 0.12 m/s. (Magnification = 920X)

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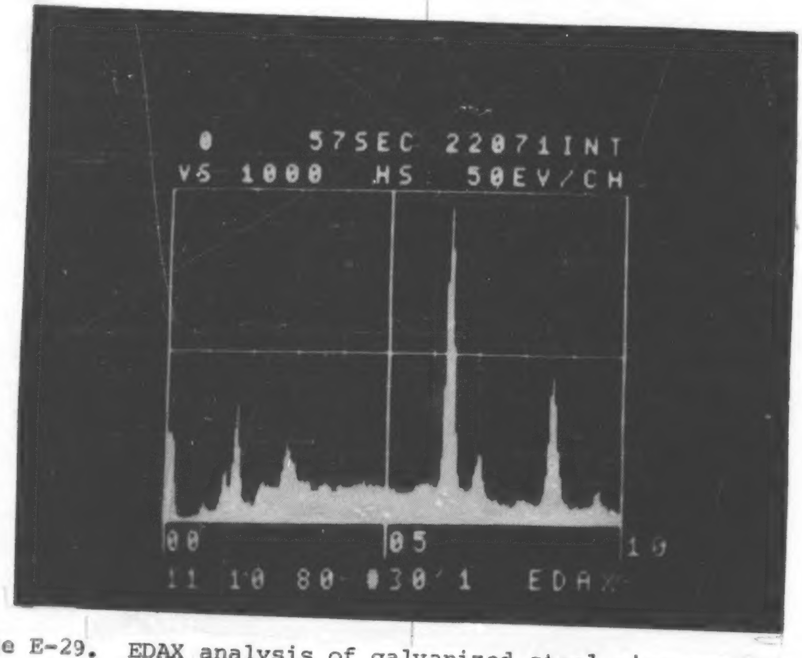

Figure E-29. EDAX analysis of galvanized steel pipe corrosion film formed under control conditions and 0.12 m/s.

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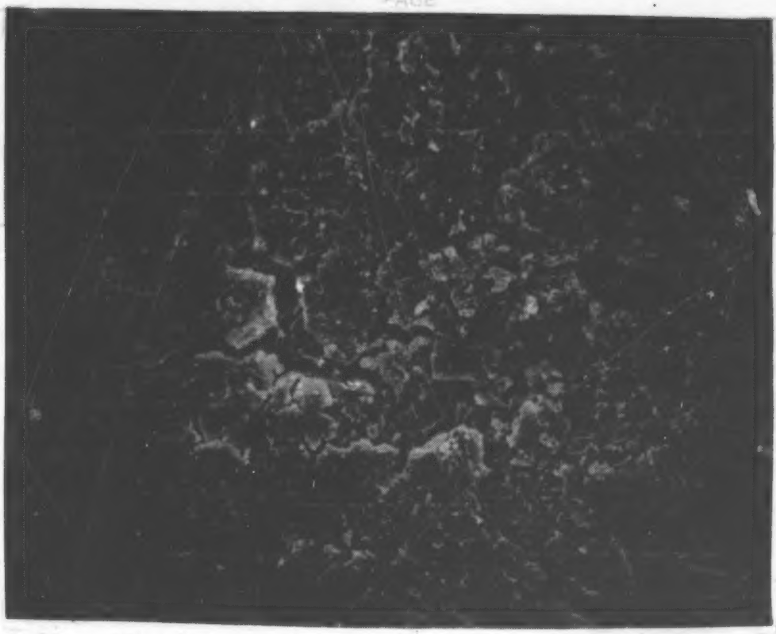

Figure E-30. SEM photograph of galvanized steel pipe corrosion film formed under control conditions and 0.18 m/s. (Magnification = 186X)

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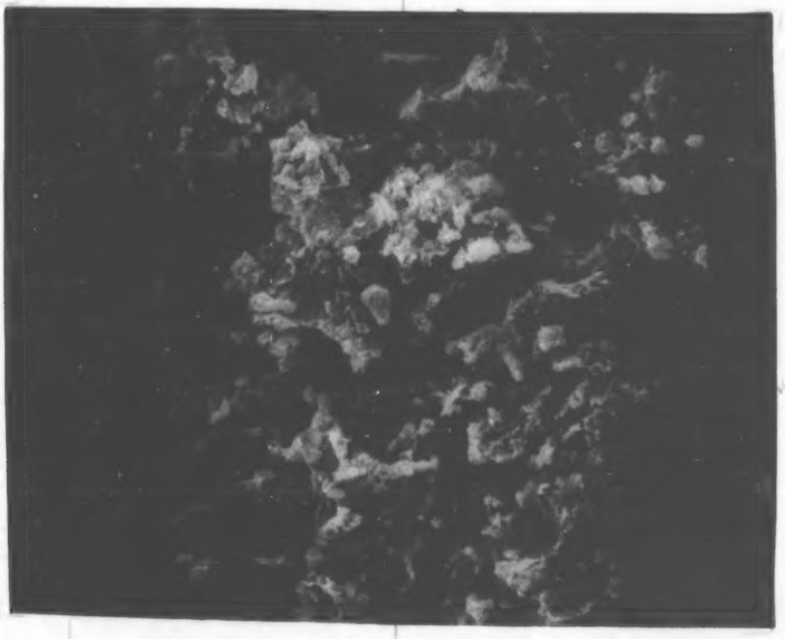

Figure E-31. SEM photograph of galvanized steel pipe corrosion film formed under control conditions and 0.18 m/s. (Magnification = 935X)

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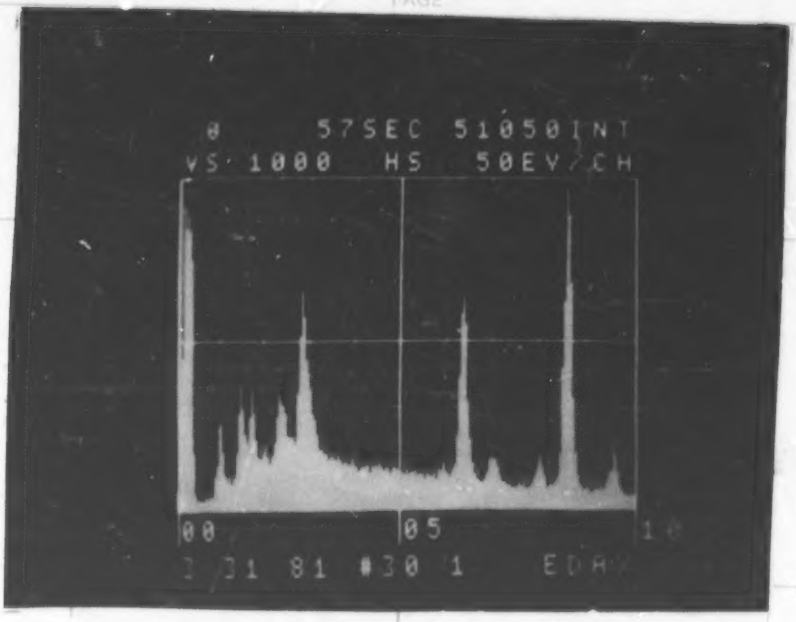

Figure E-32. EDAX analysis of galvanized steel pipe corrosion film formed under control conditions and 0.18 m/s.

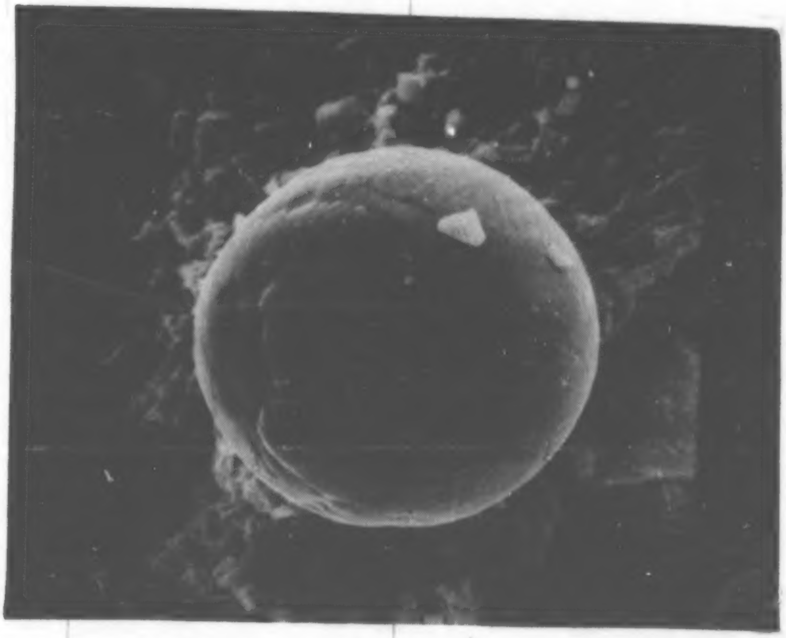

Figure E-33. Sphere on galvanized pipe surface.

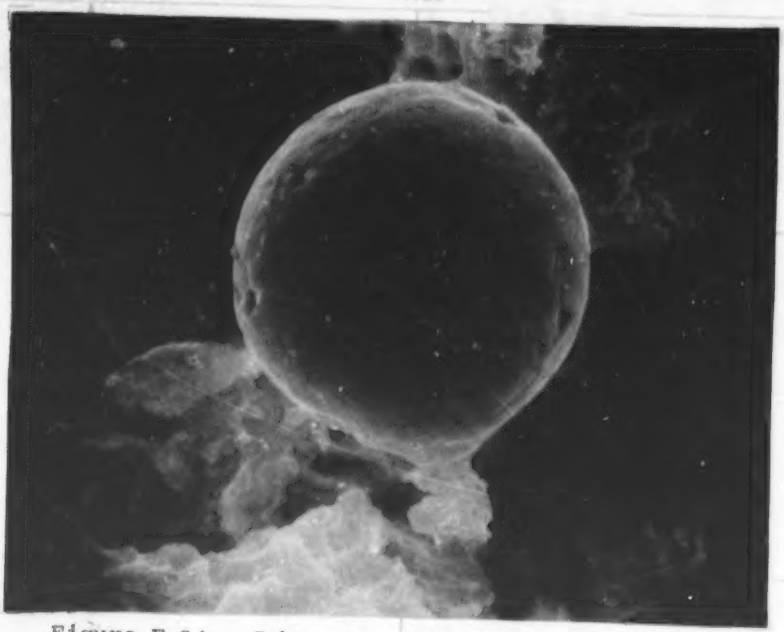

Figure E-34. Sphere on galvanized pipe surface.

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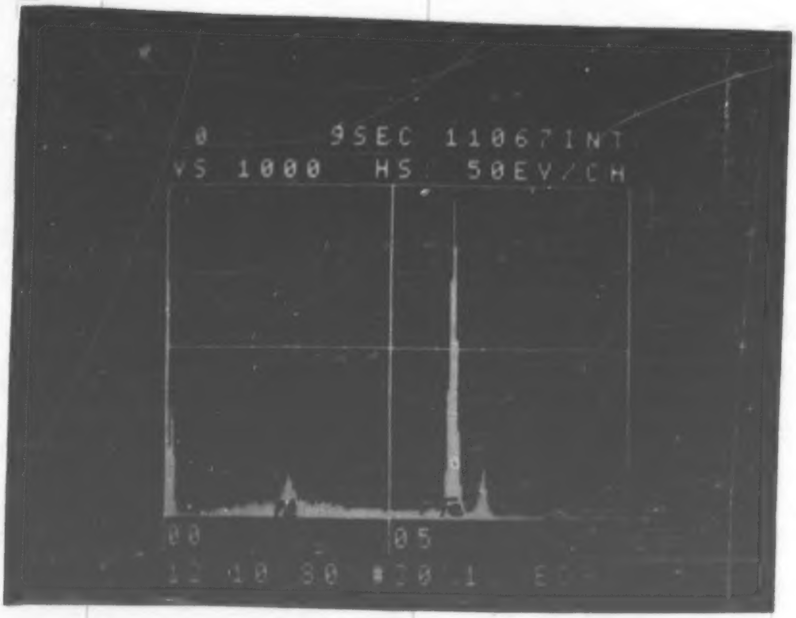

Figure E-35. EDAX analysis of sphere from pipe surface.

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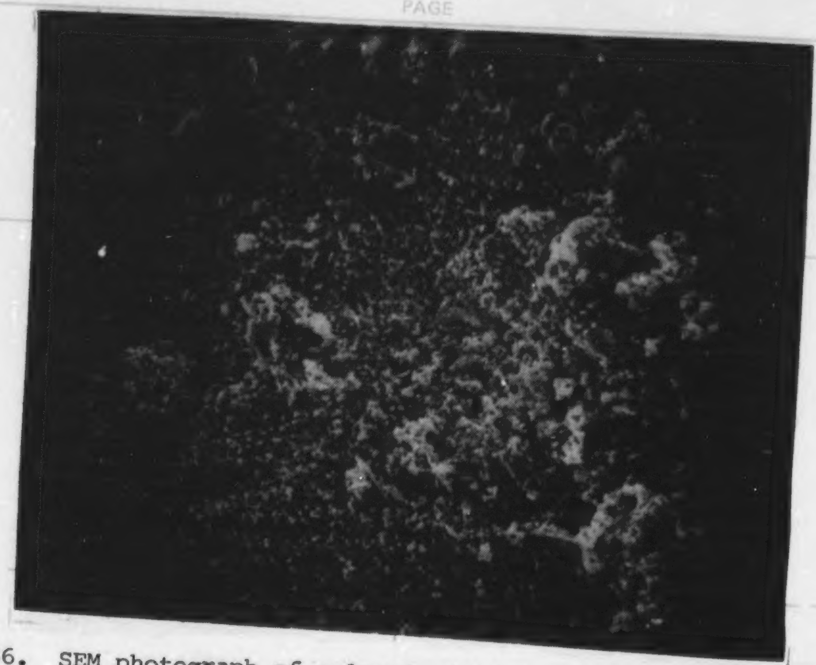

Figure E-36. SEM photograph of galvanized steel pipe corrosion film formed under lime/sodium carbonate treatment and 0.12 m/s. (Magnification = 184X)

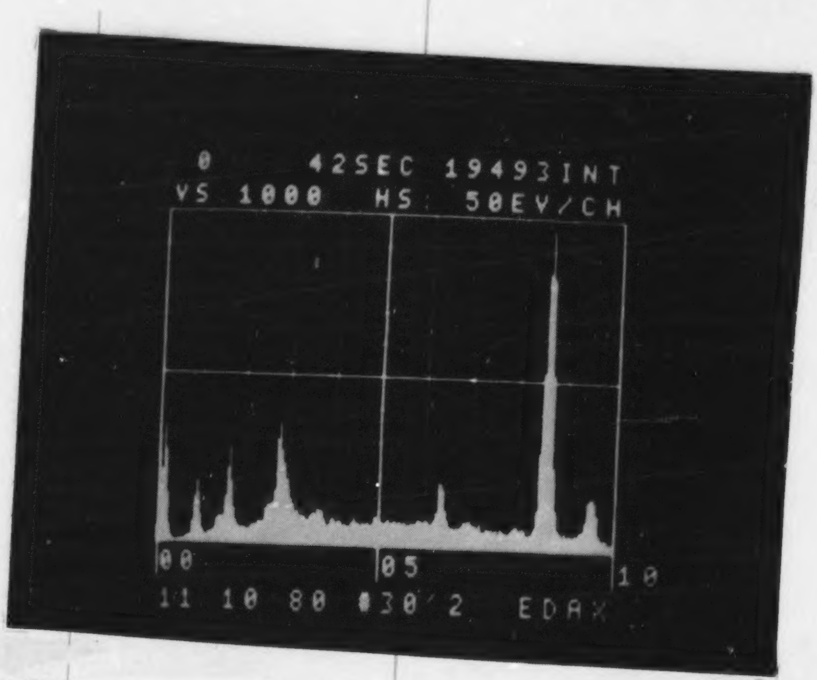

Figure E-37. EDAX analysis of galvanized steel pipe corrosion film formed under lime/sodium carbonate treatment and 0.12 m/s.

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Figure E-38. SEM photograph of galvanized steel pipe corrosion film formed under lime/sodium carbonate treatment and 0.18 m/s. (Magnification = 187X)

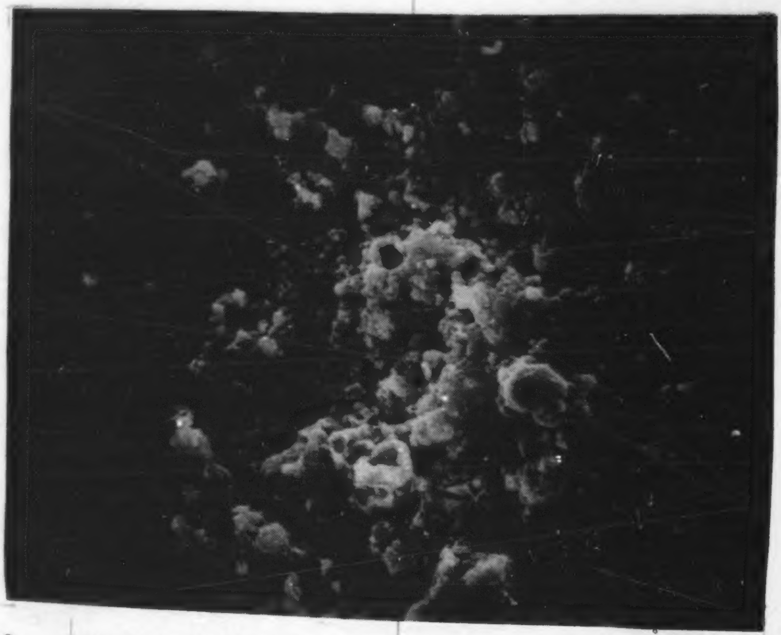

Figure E-39. SEM photograph of galvanized steel pipe corrosion film formed under lime/sodium carbonate treatment and 0.18 m/s. (Magnification = 935X)

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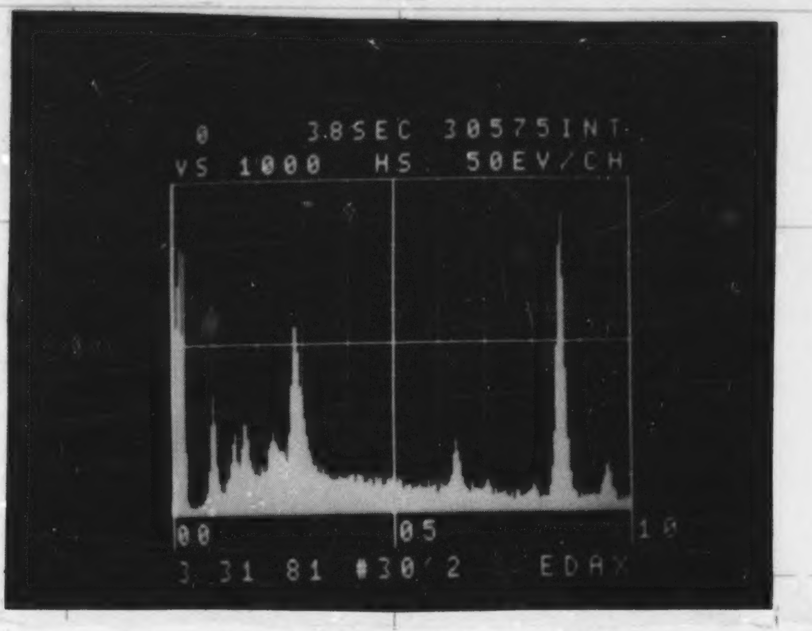

Figure E-40. EDAX analysis of galvanized steel pipe corrosion film formed under lime/sodium carbonate treatment and 0.18 m/s.

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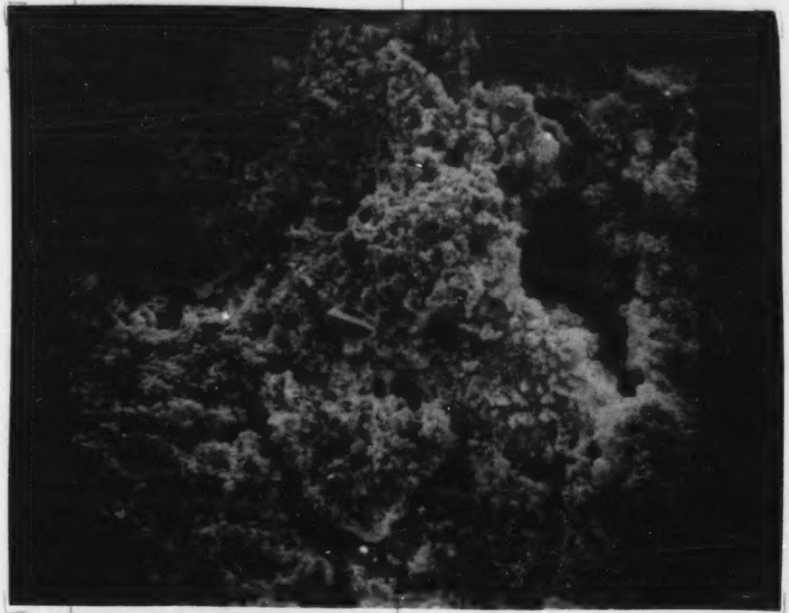

Figure E-41. SEM photograph of galvanized steel pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.12 m/s. (Magnification = 187X)

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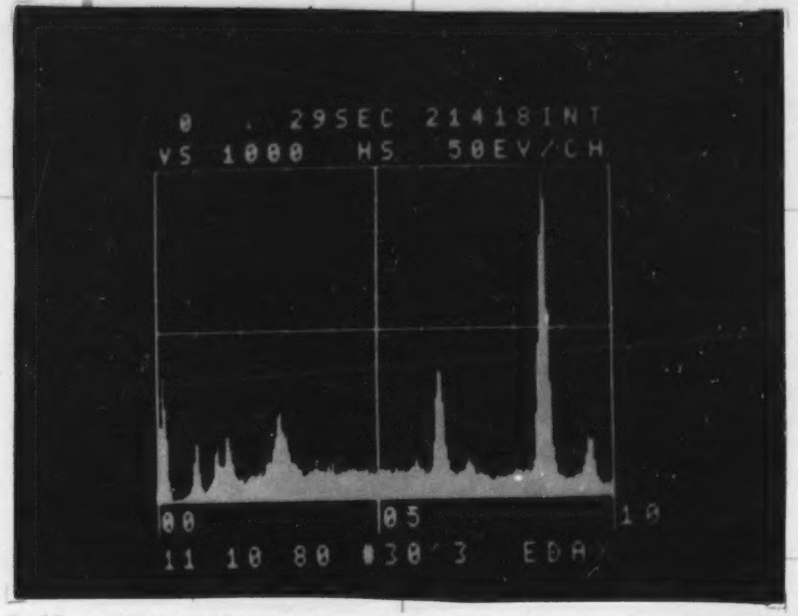

Figure E-42. EDAX analysis of galvanized steel pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.12 m/s.

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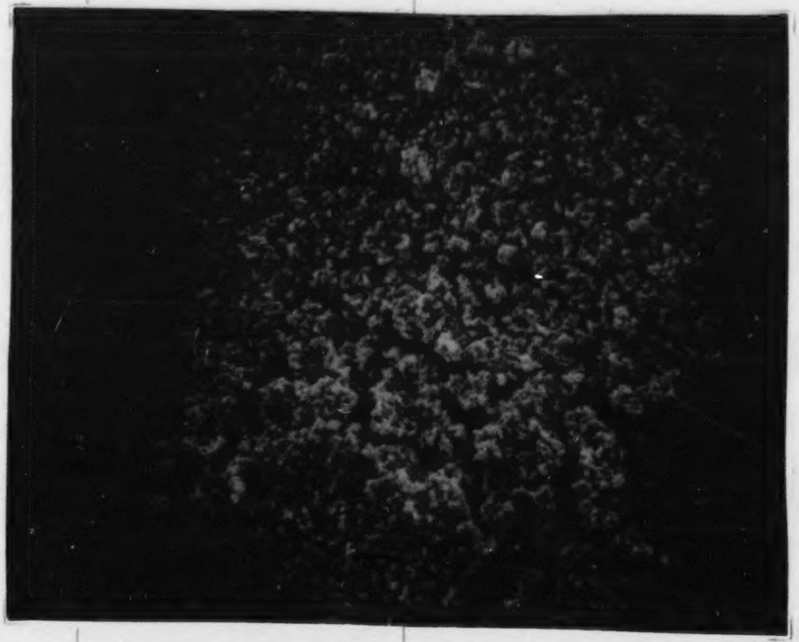

Figure E-43. SEM photograph of galvanized steel pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s. (Magnification = 185X)

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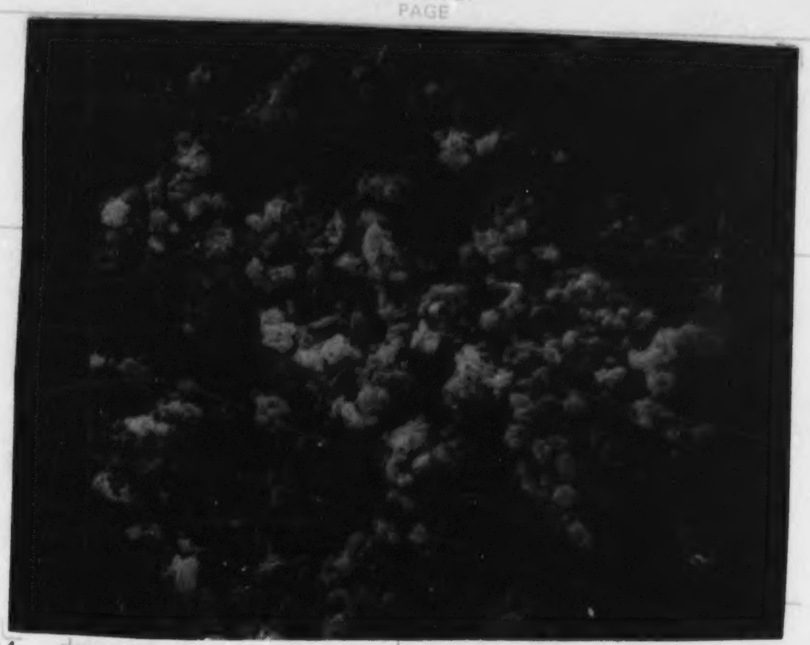

Figure E-44. SEM photograph of galvanized steel pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s. (Magnification = 930X)

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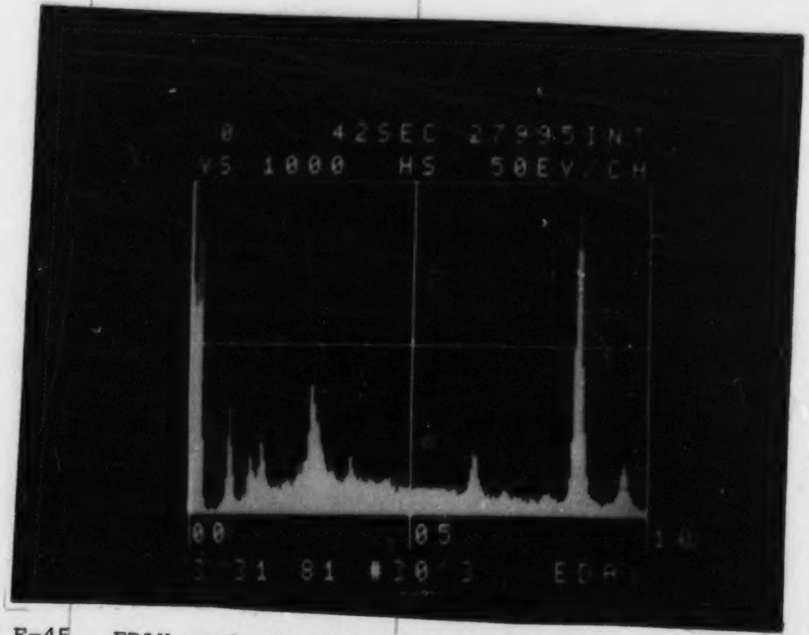

Figure E-45. EDAX analysis of galvanized steel pipe corrosion film formed under lime/sodium bicarbonate treatment and 0.18 m/s.

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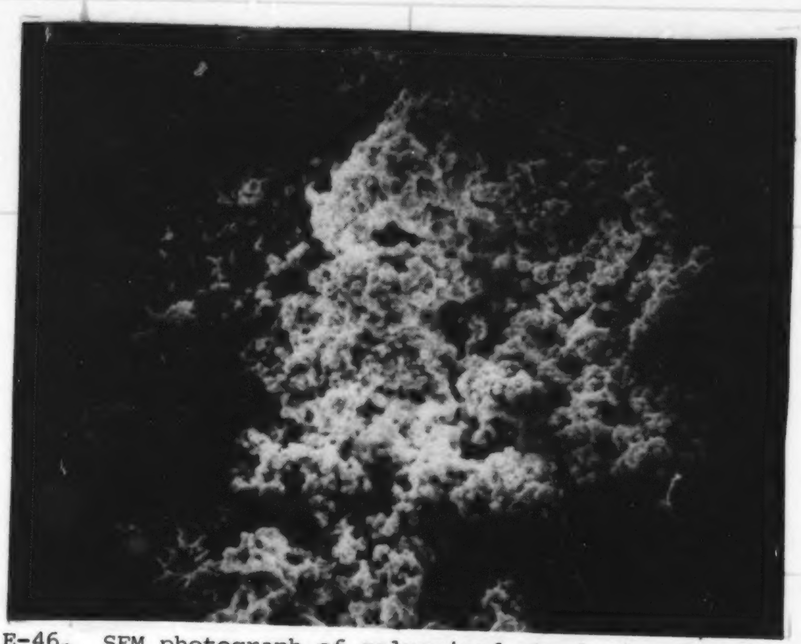

Figure E-46. SEM photograph of galvanized steel pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.12 m/s. (Magnification - 192X)

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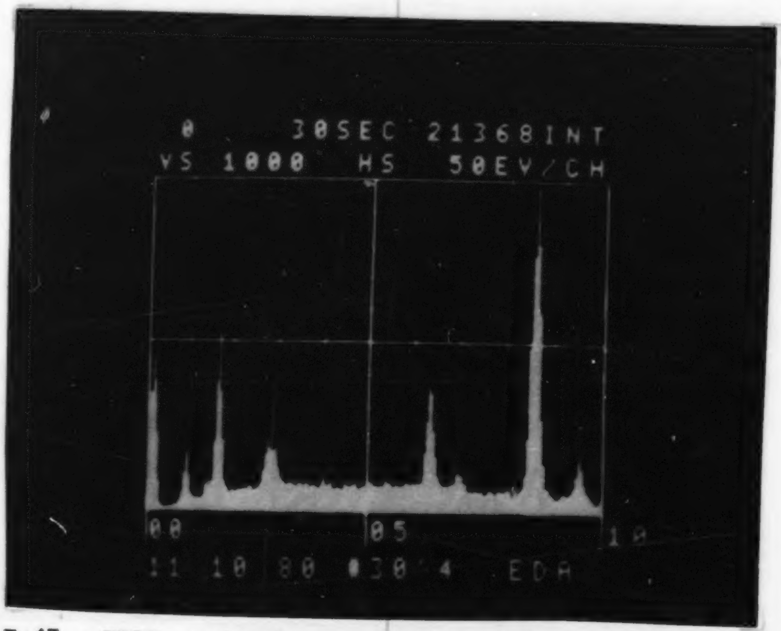

Figure E-47. EDAX analysis of galvanized steel pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.12 m/s.

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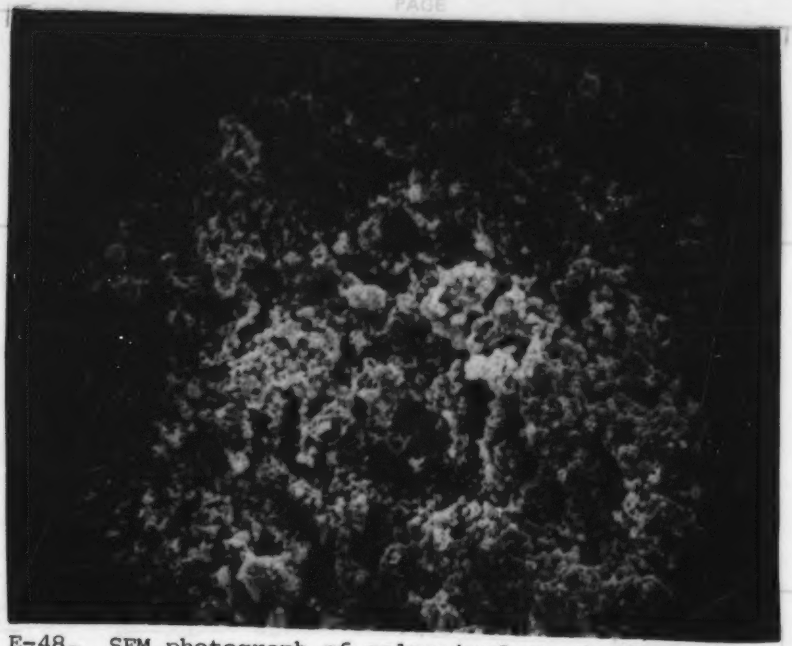

Figure E-48. SEM photograph of galvanized steel pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.18 m/s. (Magnification = 190X)

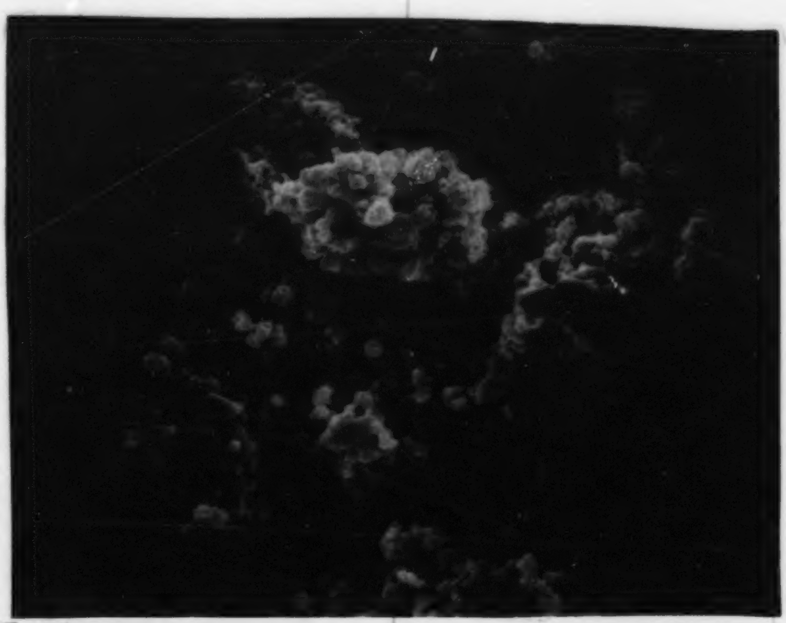

Figure E-49. SEM photograph of galvanized steel pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.18 m/s. (Magnification = 950X)

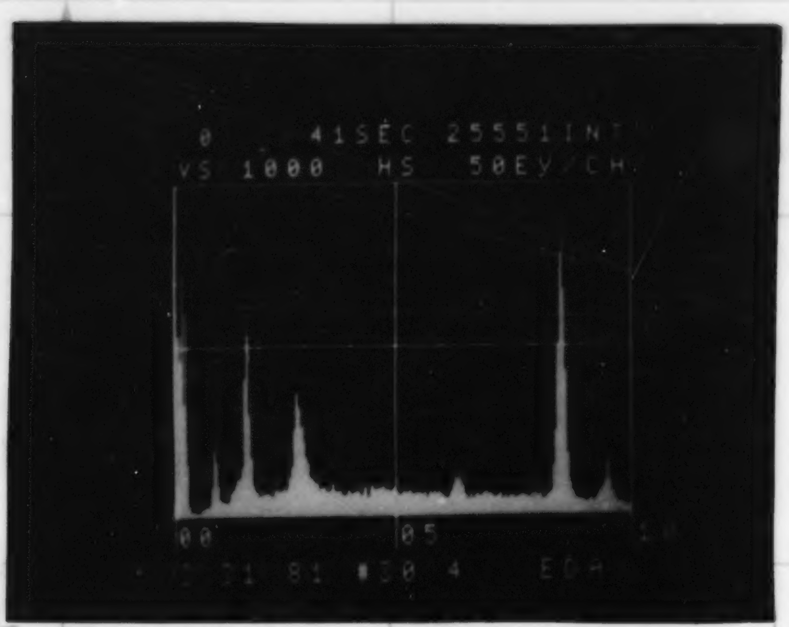

Figure E-50. EDAX analysis of galvanized steel pipe corrosion film formed under lime/bicarbonate/silicate treatment and 0.18 m/s.

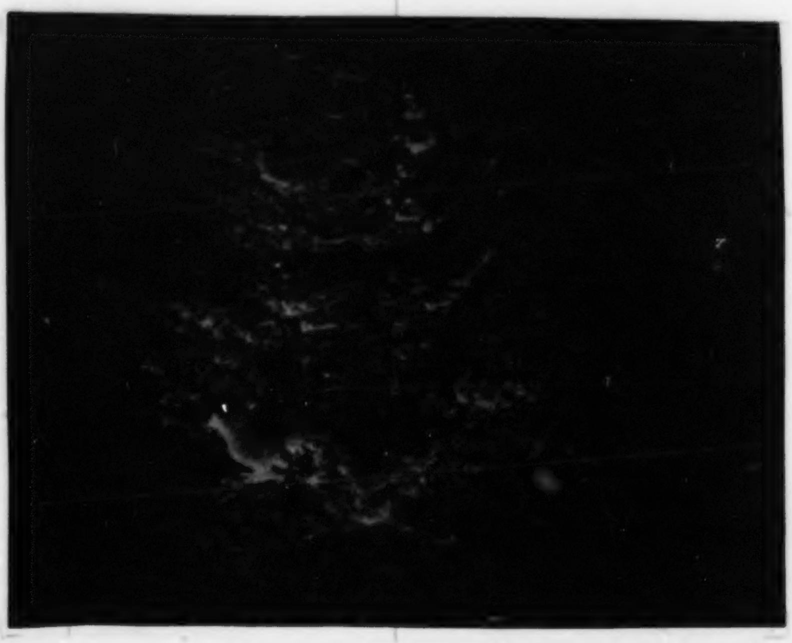

Figure E-51. SEM photograph of film formed on 50/50 lead/tin solder under control conditions and 0.18 m/s. (Magnification = 490X)

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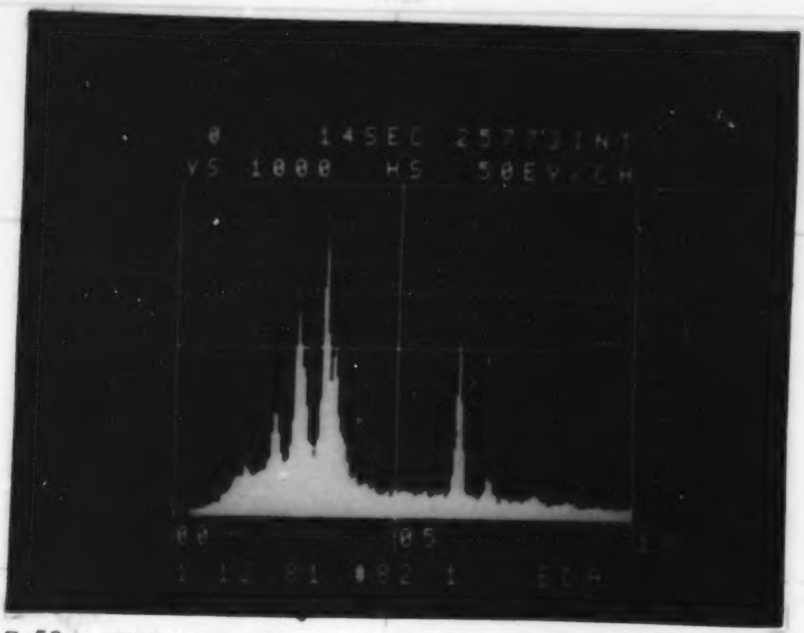

Figure E-52. EDAX analysis of film formed on 50/50 lead/tin solder under control conditions and 0.18 m/s.

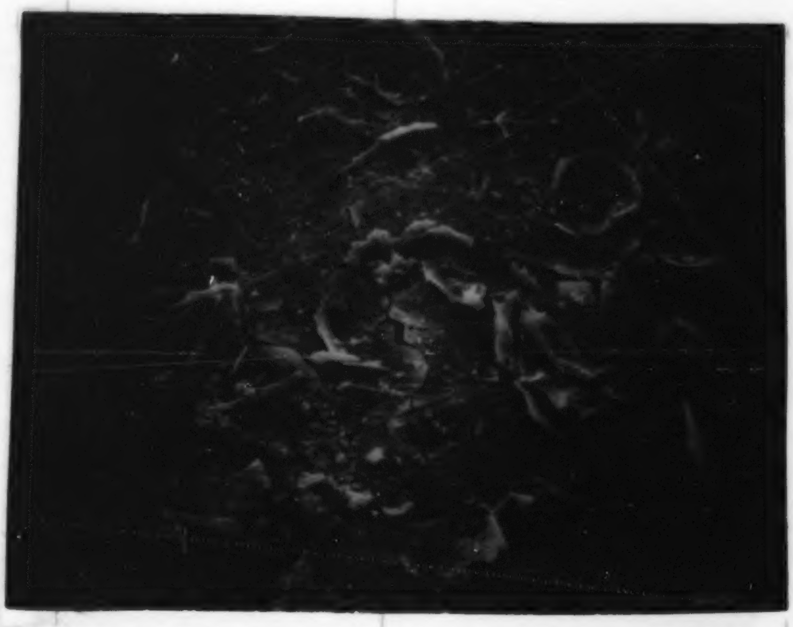

Figure E-53. SEM photograph of film formed on 50/50 lead/tin solder under lime/sodium carbonate treatment and 0.18 m/s. (Magnification = 524X)

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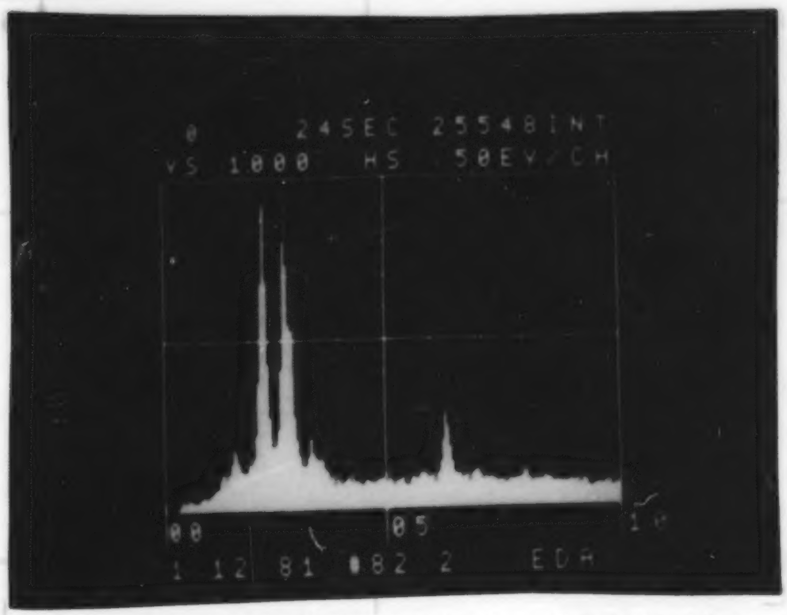

Figure E-54. EDAX analysis of film formed on 50/50 lead/tin solder under lime/sodium carbonate treatment and 0.18 m/s.

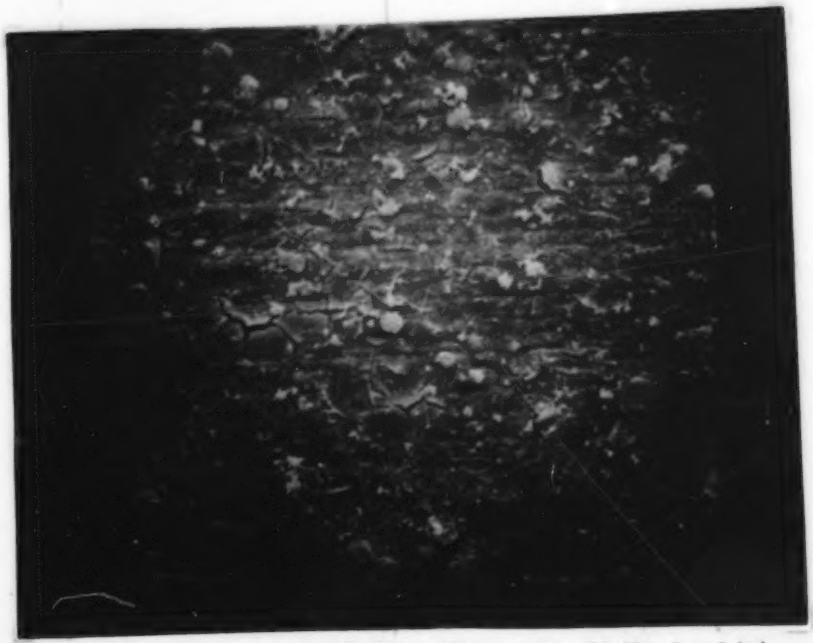

Figure E-55. SEM photograph of film formed on 50/50 lead/tin solder under lime/sodium bicarbonate treatment and 0.18 m/s. (Magnification = 510X)

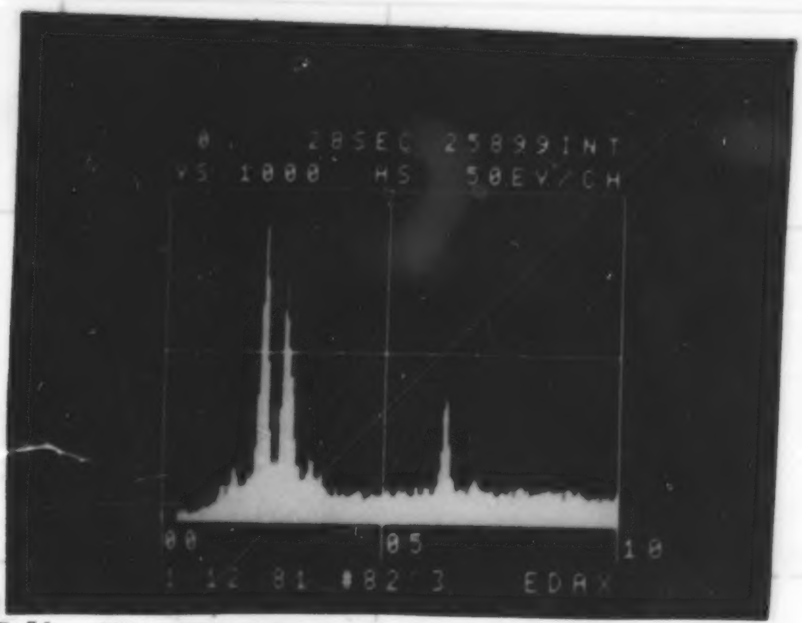

Figure E-56. EDAX analysis of film formed on 50/50 lead/tin solder under lime/sodium bicarbonate treatment and 0.18 m/s.

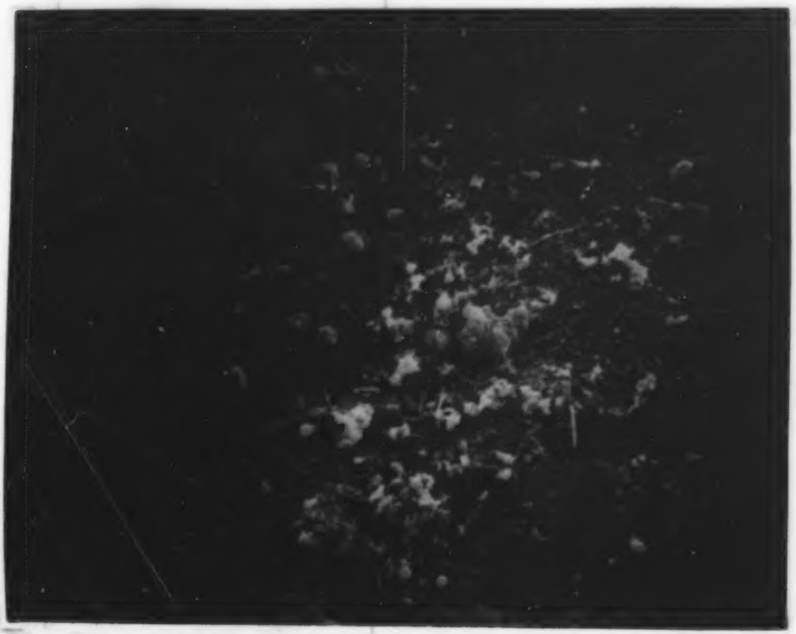

Figure E-57. SEM photograph of film formed on 50/50 lead/tin solder under lime/bicarbonate/silicate treatment and 0.18 m/s. (Magnification = 510X)

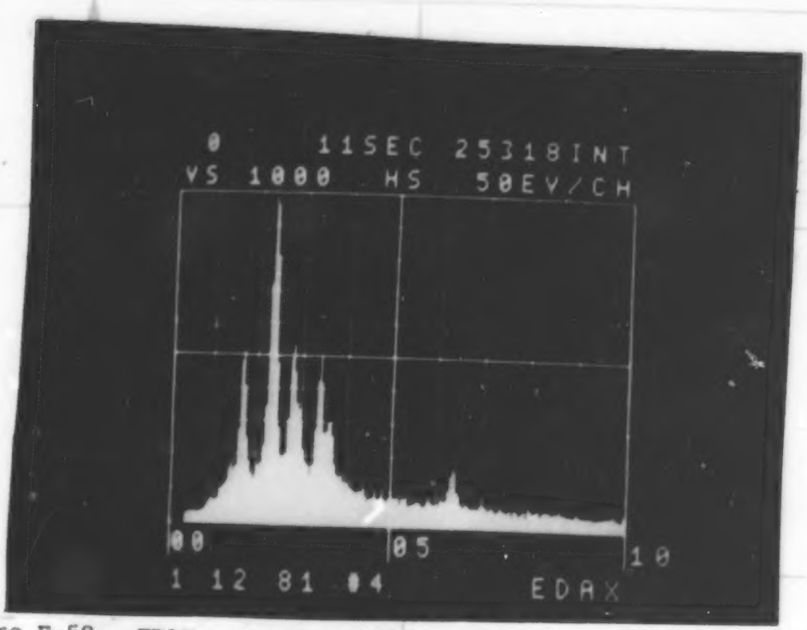

Figure E-58. EDAX analysis of film formed on 50/50 lead/tin solder under lime/bicarbonate/silicate treatment and 0.18 m/s.

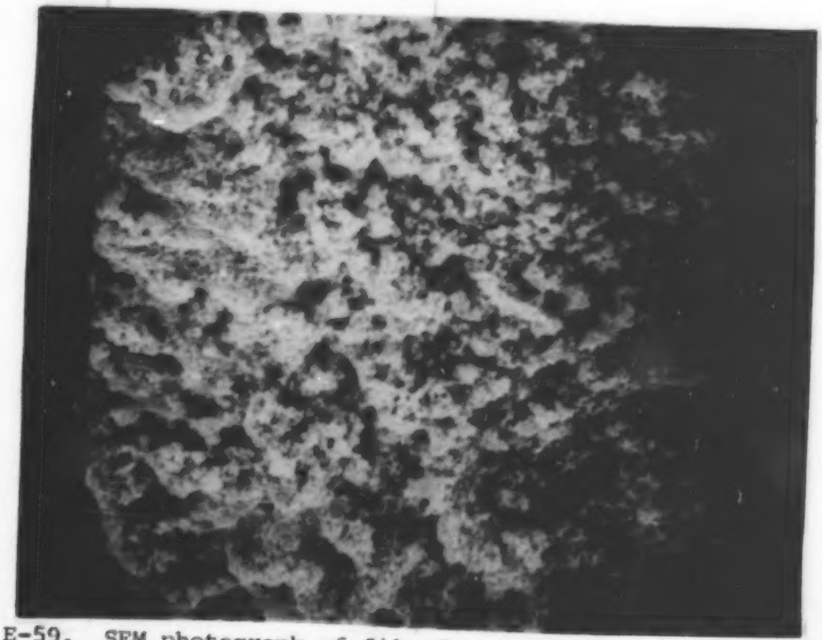

Figure E-59. SEM photograph of film formed on 95/5 tin/antimony solder under control conditions and 0.18 m/s. (Magnification = 498X)

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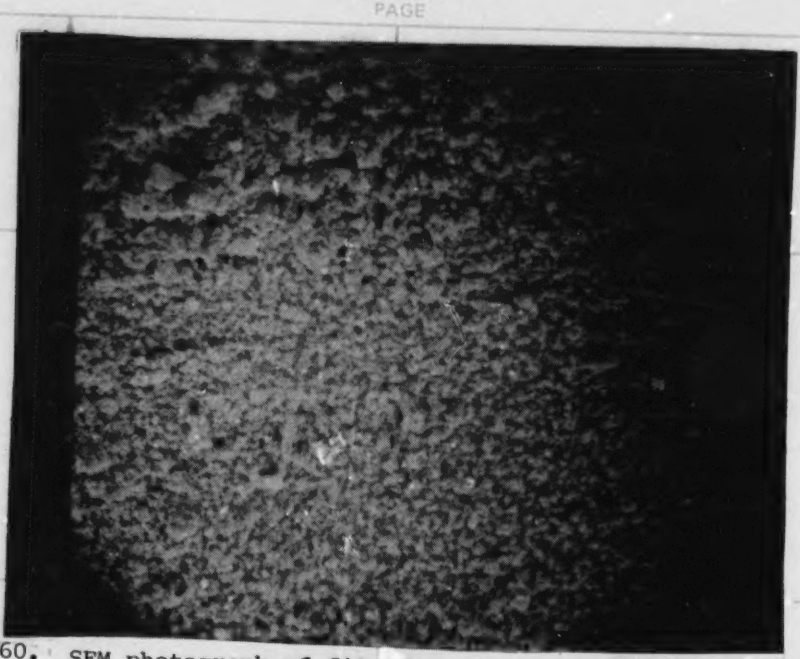

Figure E-60. SEM photograph of film formed on 95/5 tin/antimony solder under lime/sodium carbonate treatment and 0.18 m/s. (Magnification = 486X)

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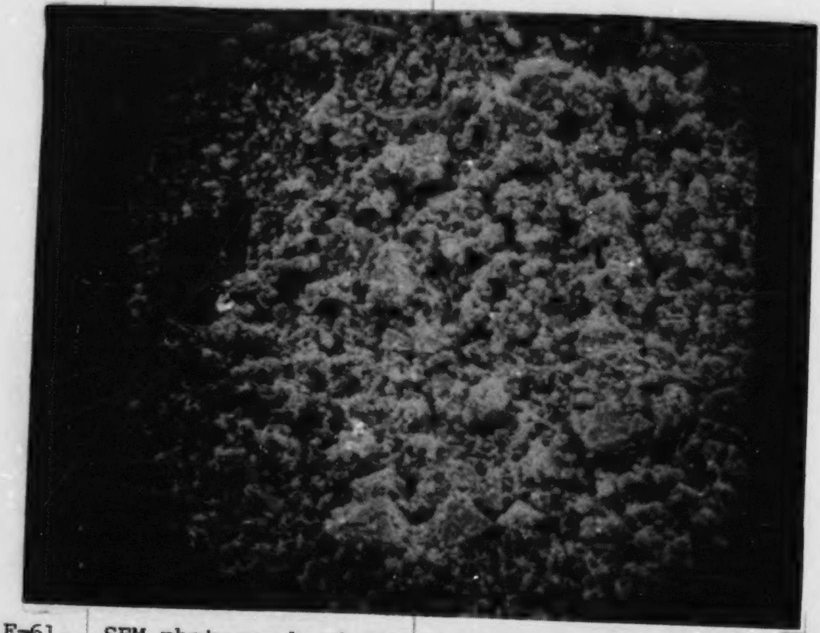

Figure E-61. SEM photograph of film formed on 95/5 tin/antimoy solder under lime/sodium bicarbonate treatment and 0.18 m/s. (Magnification = 511X)

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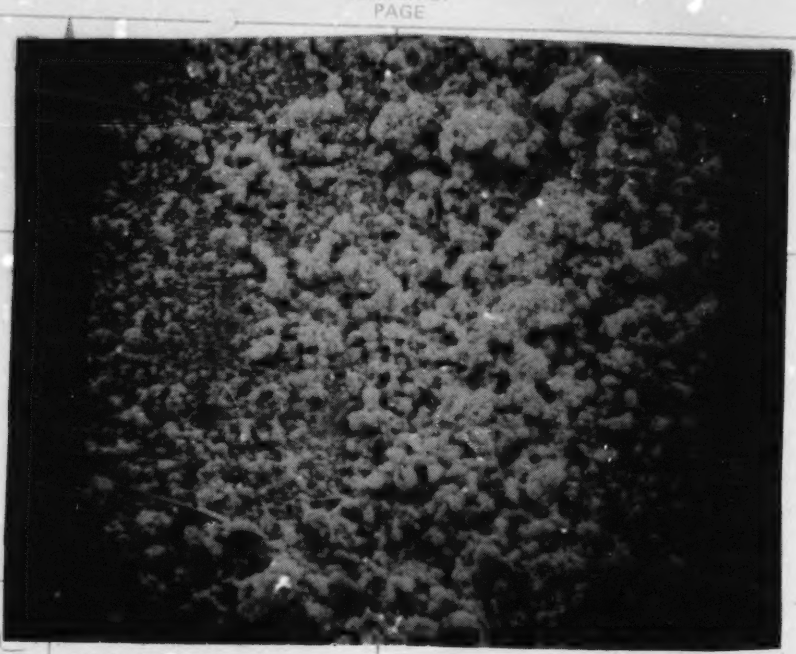

Figure E-62. SEM photograph of film formed on 95/5 tin/antimony solder under lime/bicarbonate/silicate treatment and 0.18 m/s. (Magnification = 520X)

9-1/8"

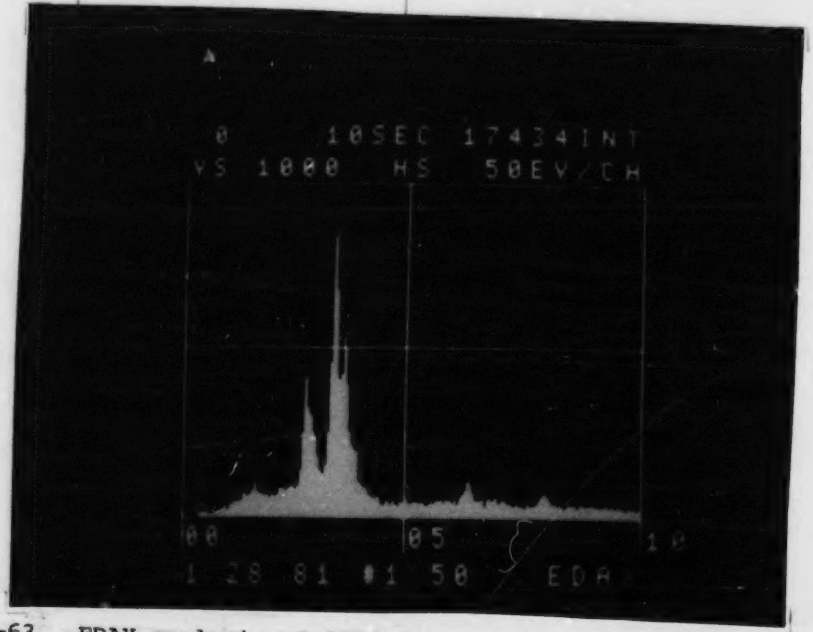

Figure E-63. EDAX analysis of film formed on 95/5 tin/antimony solder under control conditions and 0.18 m/s.

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3/8"

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

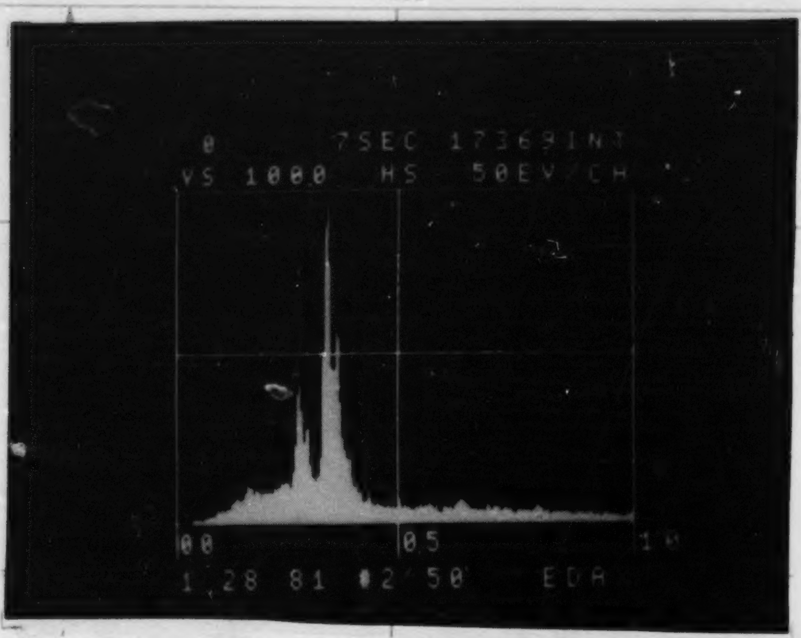

Figure E-64. EDAX analysis of film formed on 95/5 tin/antimony solder under lime/sodium carbonate treatment and 0.18 m/s.

9-1/8"

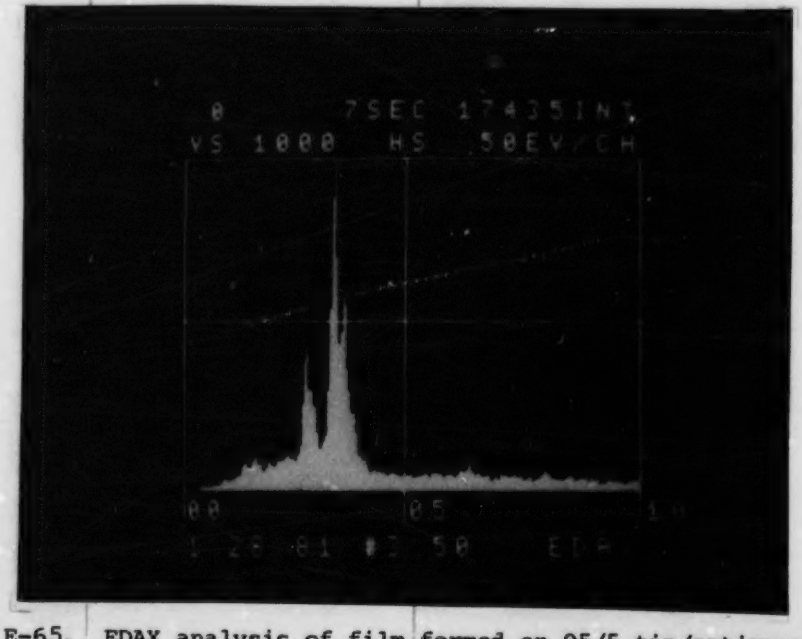

Figure E-65. EDAX analysis of film formed on 95/5 tin/antimony solder under lime/sodium bicarbonate treatment and 0.18 m/s.

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3/8"

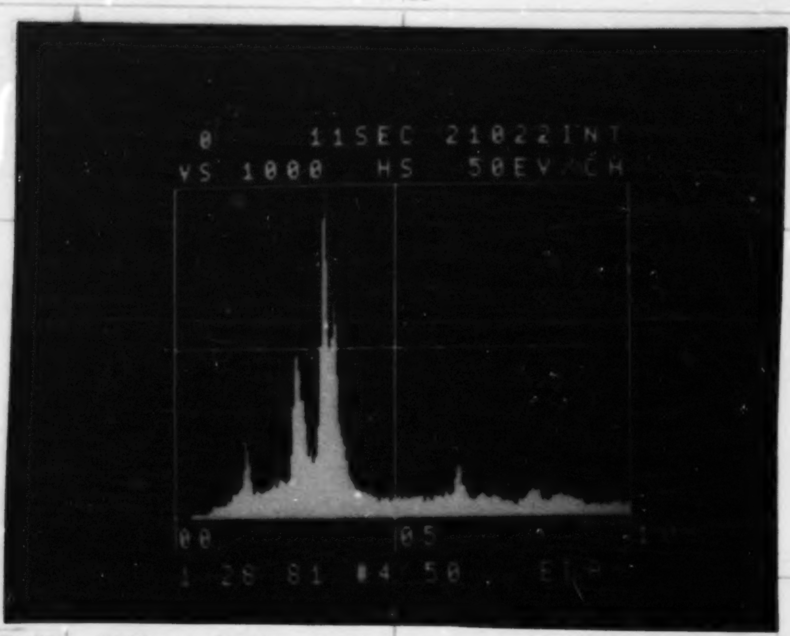

Figure E-66. EDAX analysis of film formed on 95/5 tin/antimony solder under lime/bicarbonate/silicate treatment and 0.18 m/s.

9-1/8"
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3/8"
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